Geol Survey

Geological and hydrological factors for siting hazardous or low-level radioactive waste disposal facilities

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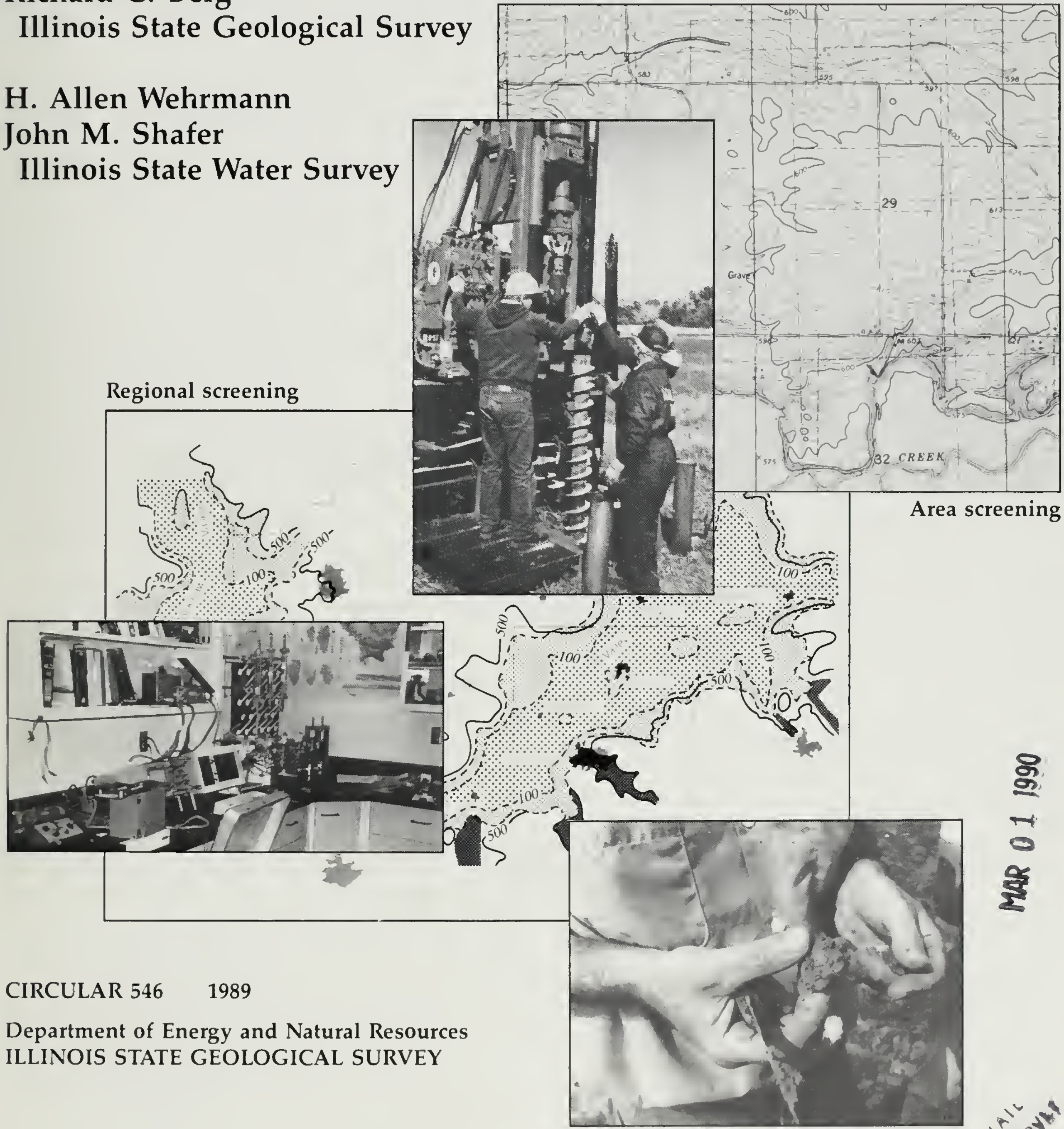

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Department of Energy and Natural Resources
ILLINOIS STATE GEOLOGICAL SURVEY

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ABSTRACT

Geological and hydrological considerations play a crucial role in the selection of sites for the disposal of hazardous waste (HW) or low-level radioactive waste (LLRW). Because it is unknown whether disposal facilities can contain these wastes securely for extended periods, disposal sites must be selected that are geologically stable, predictable, and capable of being characterized, and that contain geologic materials that present natural barriers to the migration of released contaminants. Site selection also must minimize both the long-term risk of contamination of water resources and the potential of contaminant transport through groundwater and surface-water systems.

A multistep approach for collecting and evaluating regional, area-wide, and site-specific data ensures that the broadest possible range of information will be available in the site-selection and site-characterization processes. This approach includes the review of existing data, construction of area and site maps, extensive field studies, and groundwater modeling. From this information, sites can be selected and then characterized in detail for HW or LLRW disposal.

The first step, regional directive screening, identifies areas that have a high probability of containing suitable sites. Regional factors that should be evaluated include the location of aquifers and recharge areas, groundwater flow, well or potential aquifer yields, groundwater quality, the presence of karst features, the location of undermined areas, and seismic risk. From this screening, a "probabilistic" determination can be made as to the initial suitability of certain regions and areas for disposal.

The second step is area screening, which involves the collection of geological and hydrological data within those areas selected as being favorable for site location. In this step, information and evaluations from the regional screening are verified, and a detailed investigation and mapping of the geological framework and groundwater system in the area is undertaken. Factors such as well locations, groundwater withdrawals, fault zones, fracturing and weathering of geologic materials, and the engineering properties of materials are determined and documented. This provides a more thorough understanding of the geological and hydrological setting within the area of interest.

Sites that appear favorable from the regional and area screening evaluations are then characterized in detail during the third step, site characterization. Numerous investigations and subtasks are conducted as parts of this step. Detailed maps are constructed and extensive on-site tests, including drilling, are implemented. All elements of site geology and hydrology are studied intensively. Finally, site-specific groundwater modeling is undertaken to test and evaluate site performance under various conditions. Data collected and evaluated in this step should enable siting facilitators and licensing agencies to conclude whether a site is suitable for HW or LLRW disposal and to accurately predict the potential hydrological consequences of a contaminant release.

INTRODUCTION

PURPOSE AND SCOPE OF REPORT

The disposal of hazardous wastes (HW) and low-level radioactive wastes (LLRW) is a critical nationwide concern. The siting of disposal facilities for these wastes is a lengthy, complicated process that involves numerous social, economic, political, and environmental considerations. Of primary concern is the potential for contamination of water resources from surface or near-surface disposal of HW or LLRW. The potential for such contamination is reduced when geological and hydrological conditions restrict surface and subsurface contaminant migration. Therefore, the identification of suitable geological environments for waste disposal is important. The siting process should be based on criteria that identify regions with geologic terrains that would contain a released contaminant in a manner posing the least risk to human health and the least possible impact to the environment.

Numerous approaches can be implemented to select sites. We believe the systematic and efficient methodological approach described in this paper should be followed to ensure that a geologically and hydrologically suitable disposal site is selected. We also believe that this methodological approach to site selection will be cost-beneficial, enabling recognition of potentially undesirable geological and hydrological factors early in the siting process and thereby avoiding costly site-characterization activities.

This report (1) identifies criteria important to the siting of a HW or LLRW disposal facility and recommends geological and hydrological guidelines and restrictions for siting such a facility, (2) justifies the importance of geological and hydrological criteria with regard to site performance, and (3) discusses methods of investigation for site selection and characterization. This document emphasizes aspects of siting not adequately discussed in the literature, such as the design of a geological characterization program and regional and site-specific geomorphic aspects of facility siting. It is designed to help state and local officials understand the complexities of geology and hydrology in the siting process. More importantly, it provides those responsible for site selection and characterization with a checklist of items that must be considered and understood to ensure that an environmentally safe site is selected, one in which the potential for contamination to underlying groundwater resources is low and the potential disruption of the site by natural causes is minimal.

Although this report specifically addresses the selection and characterization of sites for HW or LLRW disposal, the methodology and procedures presented here also could be applied to the siting of municipal landfills and other waste storage facilities; they could aid also in the siting of industries that are high generators of chemicals or waste products.

For the first time, a detailed discussion of the elements necessary to conduct a regional geological and hydrological investigation is presented. The need for a "regional approach" to siting was discussed by Kempton, Berg, and Soller (1989). They mentioned that the procedure has not been widely used, partly because its methods for extrapolating data are not commonly accepted by those called upon to deal with site-specific problems that require the rapid gathering and interpretation of geological and hydrological data. However, to understand and interpret site-specific hydrogeological data, the regional geological framework must first be constructed. This significantly improves the ability of siting investigators to predict the occurrence and distribution of aquifers and helps in determining local and regional groundwater flow systems.

This report focuses on the long-term protection of water resources. Other criteria of importance to the siting process, such as sociological, cultural, or political factors, are not discussed. Although specific inferences and figures used in this document relate to the siting of HW or LLRW disposal facilities in Illinois, the methodology for siting such a facility and the procedures used for siting and site characterization can be applied to most geographic regions. Illinois is used only as an example.

We have based this report on the assumption that one cannot predict whether an engineered waste containment structure or facility will endure natural hazards of normal weathering and degradation over an extended waste containment period. Therefore, to ensure that wastes would not migrate off the site in the event of a release, there must be reliance on natural earth materials and the local geological and hydrological setting.

We are not discounting the importance of properly engineered disposal systems. On the contrary, we believe that geology/hydrology and engineering principles of site selection and design both should be optimized. That is, if the engineered containment structure fails, resulting in leakage of hazardous substances, geological and hydrological properties of earth materials should be able to prevent the transmission of contaminants to groundwater and surface-water resources. Similarly, the engineered structure should be designed under the assumption that the geological and hydrological setting may not perform as predicted. When the site is selected, the design of the proposed waste containment facility and how it would affect the local setting must also be taken into account in determining the overall suitability of the site for disposal. On-site characterization and modeling of potential contaminant flow patterns will ultimately determine the likelihood of groundwater contamination.

METHODOLOGICAL OUTLINE

Many of the geological and hydrological criteria discussed in this report are interrelated. The format selected is intended to reduce overlap between discussions of individual siting criterion. A logical approach for selecting a candidate waste disposal site or sites and then characterizing the site(s) involves a multi-faceted procedure, with each step related to and building on knowledge gained from results and findings in previous steps (table 1). The approach is divided into three major steps:

1) regional directive screening
2) area screening
3) site characterization

Regional directive screening uses statewide data to provide a broad overview of geological and hydrological conditions; this helps direct the siting of a waste disposal facility to those regions having the greatest probability of containing a suitable site. Regional directive screening is based on mapping that is probabilistic; therefore, most geological or hydrological conditions depicted on statewide maps must be verified through area screening and site characterization. Area screening and site characterization are also basically mapping exercises; however, the scale at which the information is depicted is considerably larger than for the regional screening.

Knowledge of the statewide geological and hydrological setting is needed to (1) suggest regions where disposal will have the minimum potential for contamination of surface-water and groundwater resources, (2) provide the necessary regional hydrogeological framework for more detailed site characterization, (3) provide a preliminary estimate of the variability of geologic materials at a particular site, and (4) locate regions of potentially valuable nonrenewable resources, the removal of which could affect the integrity of a disposal facility. Regional data and maps cannot replace detailed on-site investigations but greatly aid in the preliminary design of evaluation programs for specific sites.

Area screening involves the collection of data within and adjacent to candidate sites, which are located in regions found favorable by the regional screening. Sites that appear favorable from the area screening are then characterized in detail. This process should result in the early dismissal of sites judged potentially suitable on a regional scale but then found unsuitable on a smaller scale.

Each step of the methodology is further subdivided into investigative elements (geological or hydrological) that should be studied. Some of the elements are investigated during more than one of the steps, depending on the scale of investigation (for example, determining the presence of aquifers and other highly permeable materials).

Recommendations are procedural and/or proscriptive. Procedural recommendations suggest and discuss particular methodologies for determining and/or conducting tasks. Proscriptive recommendations sug-

Table 1. Siting steps and investigative elements.

Siting step	Investigative elements
Regional directive screening	Regional geologic framework and aquifer mapping Recharge areas Regional groundwater flow Well/potential aquifer yields Groundwater quality Regional karst features Regions of undermined areas Areas of seismic activity
Area screening	Site topography/slope stability Geologic framework and aquifer mapping Well inventory Groundwater withdrawal Presence of strongly weathered materials Fault zones Fracturing of geologic materials Engineering properties of geological materials Local karst features Mineral resources Mined areas
Site characterization	Base map construction Geologic map construction Landscape stability Mass movement susceptibility Remote sensing and geophysical exploration Drilling program Stratigraphy Structural features Material weathering Homogeneity/isotropy Engineering properties Geochemical considerations Flood hazard areas Surface water body proximities Groundwater flow considerations Groundwater monitoring program Vadose zone studies Groundwater modeling

gest whether a waste disposal facility should or should not be sited based on the absence or presence of a particular geological or hydrological characteristic. Many of the recommendations for investigative elements are both procedural and proscriptive.

Many recommendations suggested in this document are likely to result in lengthy investigations. For example, the U.S. Nuclear Regulatory Commission (USNRC) estimates that a minimum of 1 year is needed to collect data to determine groundwater level fluctuations and a water budget for a candidate LLRW disposal site (Siefken et al., 1982). Although these investigations may at times appear costly, time-consuming, and overly conservative in terms of environmental protection, they should not be shortened. The goal of our recommendations and suggestions is to ensure that a site proposed for HW or LLRW disposal is stable and capable of meeting performance objectives.

LITERATURE REVIEW

An extensive literature search for documents pertaining to the siting of HW or LLRW disposal facilities was conducted prior to the development of this report. This search resulted in the identification of numerous reports that list or discuss criteria important to site selection, characterization, and performance. Of major interest are the following reports: Siefken et al. (1982); EG&G Idaho, Inc. (1984); Illinois Department of Energy and Natural Resources (1984); New York State Energy Office (1984); Committee of the Massachusetts Executive Office of Environmental Affairs (1985); Monnig (1984); Doucette (1984); and the U.S. Environmental Protection Agency (1984). Texts presenting more in-depth discussions of individual geological and hydrological criteria were also obtained and reviewed. These included texts by Baker, Kochel, and Patton (1987), Blatt et al. (1980), Dunne and Leopold (1978), Freeze and Cherry (1979), Holtz and Kovacs (1981), Rib and Liang (1978), Ritter (1978 and 1986), Schumm (1977), and Wells et al. (1985). Much of the information from these documents has been incorporated into this report.

This document was prepared primarily by combining three reports that were developed for the Illinois Department of Nuclear Safety by the ISGS and the ISWS for purposes of establishing criteria and a methodology for selection of a LLRW disposal facility in Illinois (Miller et al., 1985; Berg et al., 1989a; and Berg et al., 1989b). Geological and hydrological criteria for siting a HW disposal facility are essentially the same as those for siting a LLRW disposal facility.

REGIONAL DIRECTIVE SCREENING

INTRODUCTION

Regional directive screening, the first step in the selection of a HW or LLRW disposal site, is a key component in statewide waste disposal planning. The screening evaluates regional geological and hydrological information to determine the presence of potentially severe environmental problems at prospective sites. This step is important because it directs the siting of a disposal facility away from areas known to be hydrogeologically vulnerable to contaminant release, thus reducing the long-term risks of groundwater and surface-water contamination. "Regional" refers generally to a state or county; in most cases, siting efforts are confined within one of these boundaries. However, because of the nature of groundwater systems, site screening often must include the consideration of geological and hydrological factors beyond state and county boundaries.

Regional directive screening includes the evaluation of regional geological and hydrological mapping. This provides information about the possible variability and predictability of geologic materials at a candidate site and about groundwater flow conditions that can be expected. In general, the more variable that the geological and hydrological conditions are regionally, the more extensive the subsurface exploration program must be to evaluate the geological and hydrological setting of a site. Detailed accounts of the use of regional data for waste or resource planning are presented in Berg, Kempton, and Cartwright (1984a); Kempton (1981); Kempton and Cartwright (1984); Kempton, Soller, and Berg (1987); and Soller (1987).

Primary emphasis in this step is focused on identifying (1) the distribution of groundwater resources and (2) highly permeable materials with the capability of rapidly transmitting contaminants (i.e., sands and gravels, sandstones, and fractured dolomites and limestones—materials with hydraulic conductivities exceeding 1 x 10^{-4} cm/sec). Secondary emphasis is placed on delineating the location of nonrenewable resources (e.g., coal, sand, and gravel).

Geological and hydrological elements that should be evaluated and mapped as a part of the regional directive screening process include:

- permeable materials with high hydraulic conductivities within 90 meters of ground surface
- regional recharge areas
- regional groundwater flow direction
- well yield/potential aquifer yield
- regional groundwater quality
- regional karst areas
- mined areas
- seismic risk areas.

REGIONAL GEOLOGICAL FRAMEWORK AND AQUIFER MAPPING

The principal goals of reviewing the regional geological framework and aquifer mapping are: (1) the establishment of the regional geological framework, (2) the delineation of groundwater resources, and (3) the delineation of permeable materials with the capability of rapidly transmitting contaminants. The mapping of geological conditions and materials with high hydraulic conductivities on a statewide basis is probabilistic; portions of a state mapped as containing unacceptable materials cannot be excluded from consideration for HW or LLRW disposal without area screening and site characterization. However, regional screening for the presence of these materials can greatly reduce the potential for encountering problem areas and increase the probability of locating an acceptable site.

The presence of aquifers may indicate a hydrogeological environment conducive to rapid groundwater movement, and it is necessary that such an environment be separated from potential contaminants by thick sequences of relatively impermeable materials. In addition, groundwater withdrawals from an aquifer now or in the future may affect the rate, direction, and predictability of groundwater movement, increasing the risk that groundwater and groundwater users will be exposed to wastes.

In general, rates of contaminant migration increase with increasing permeability (hydraulic conductivity) of geologic materials. Earth materials defined as aquifer or potential aquifer units typically have higher hydraulic conductivities and may transmit contaminants more rapidly than adjacent, less permeable geologic units. As a result, the horizontal and vertical distribution of released contaminants will be influenced, within the limitation of groundwater flow, by the distribution and thickness of highly permeable units.

In addition, the design of a groundwater monitoring program (i.e., spacing, depth, and number of monitoring wells) is dependent upon the size and geometry of highly permeable units. Other permeable materials (e.g., fractured dolomite or sandy tills) that have a high potential to transmit contaminants may not be aquifers, but they may provide the medium for migration of contaminants to a groundwater or surface-

Table 2. Summary of major aquifer units in Illinois from youngest to oldest. Major aquifers are defined as units that can yield 300 or more liters of water per minute.

Unit name	Character
1. Quaternary sand and gravel	Unconsolidated sand and gravel
2. Hunton Limestone Megagroup Middle Devonian Series Lower Devonian Series Cayugan Series (Silurian) Niagaran Series (Silurian) Alexandrian Series (Silurian)	Consists predominantly of Silurian and Devonian limestones and dolomites
3. Ancel Group (Ordovician) Glenwood Fm. (northern Illinois) Joachim Dol. (southern Illinois) Dutchtown Ls. (southern Illinois) St. Peter Sandstone	Consists of sandstone and argillaceous limestone and dolomite
4. Prairie du Chien Group (Ordovician) Shakopee Dolomite New Richmond Sandstone Oneota Dolomite Gunter Sandstone	Consists predominantly of cherty dolomites and interbedded sandstones
5. Ironton-Galesville Ss. (Cambrian) Iron Sandstone Galesville Sandstone	Consists of fine- to coarse-grained sandstones
6. Elmhurst-Mt. Simon Ss. (Cambrian) Elmhurst Sandstone Mt. Simon Sandstone	Composed of a coarse-grained, partly conglomeratic sandstone

water source. Therefore, for regional and site-specific mapping purposes, they are mapped along with aquifers.

This mapping is based on a simple principle: The potential contamination of highly permeable materials is dependent upon their depth, distribution, and thickness. For example, thick, extensive aquifers close to the surface are more susceptible to potential contamination than thin, small, and/or restricted aquifers deep beneath the surface. The depth to an aquifer or other highly permeable material is the distance from the lower boundary of the waste to the shallowest highly permeable material. This depth reflects the vertical distance that leachate must travel prior to reaching a highly permeable material. The depth to the shallowest permeable material, as well as the hydrogeological characteristics of materials between the waste and the material, influences the time of travel, dispersion, dilution, waste attenuation, and, hence, the amount of contaminants (if any) reaching a potential groundwater resource.

Establishing the framework. The establishment of the regional geological framework and the mapping of highly permeable materials (including aquifers or potential aquifers) provides planners and siting facilitators with a basic understanding of the geological and hydrological conditions and the continuity of specific materials at candidate sites. In many states or regions, aquifers, potential aquifers, and other permeable materials have been studied in detail, and areal boundaries and material thicknesses have been delineated and documented.

Regions where these materials are extensive probably should be excluded from consideration for HW or LLRW disposal, for they offer little or no natural barrier to contaminant movement should the engineered containment system fail. In other states or regions, the geological framework is not well known, and the presence of materials capable of rapidly transmitting contaminants may be mapped almost entirely on the basis of extrapolations from other areas. Therefore, area and site studies in these regions are essential for locating highly permeable materials.

Numerous geological and hydrological studies provide the necessary information required for regional aquifer mapping. In Illinois, for example, studies include: Berg, Kempton, and Cartwright (1984a); Bergstrom et al. (1968); Burris, Morse, and Naymik (1981); Kempton, Morse, and Visocky (1982); Pryor (1956); Sanderson and Zewde (1976); Sasman et al. (1982); Schicht (1965); Selkregg and Kempton (1957, 1958); Smith and Larson (1948); Suter et al. (1959); Visocky, Sherrill, and Cartwright (1985); Walker, Bergstrom, and Walton, (1965); and Zeizel et al. (1962).

Mapping the distribution of aquifers and other highly permeable materials. Information should be compiled to map all known highly permeable materials in regions larger than 1 square kilometer. In Illinois, for example, major aquifers are defined as geologic units (sand and gravel or fractured and/or permeable bedrock) capable of yielding at least 300 liters of water per minute to wells completed in them (a designation consistent with the Illinois Water Use Act of 1983). Minor aquifers are defined as sand and gravel deposits at least 1.5 meters thick, sandstone units at least 3 meters thick, or carbonate rocks at least 4.5 meters thick that typically yield between 20 to 300 liters of water per minute. Aquifers must contain only potable water, defined for our purpose as water containing less than 2,500 mg/L total dissolved solids.

Major bedrock aquifer units (table 2) were mapped according to their depth. That is, major bedrock aquifers containing potable water were independently mapped to show the distribution of aquifers within 90 meters of ground surface. Also produced were maps showing the distribution of aquifers (major and minor) and other highly permeable materials within 15 meters of ground surface and the distribution of major sand and gravel aquifers at any depth in Illinois.

Maps showing aquifers and other highly permeable materials within 15 meters of the surface, major sand and gravel aquifers at any depth, and major bedrock aquifers within 90 meters of the surface were combined to present a composite statewide map that directs siting to regions lacking these features. Minor sand and gravel aquifers between depths of 15 and 150 meters are not included in this statewide screening assessment because of the complexity required to conduct such mapping. However, these aquifers should be mapped as part of the site characterization process discussed later.

Major and minor aquifers and other highly permeable materials within 15 meters of ground surface in Illinois are shown in figure 1. This map was modified from Berg and Kempton (1984). Aquifers and other highly permeable materials shown on this map are defined according to lithology; only sand and gravel units at least 1.5 meters thick, sandstone at least 3 meters thick, and fractured limestone or dolomite at least 4.5 meters thick with a lateral extent of at least 1 square kilometer are included.

The distribution of major sand and gravel aquifers at any depth in Illinois is shown in figure 2. Major sand and gravel aquifers are generally found within pre-glacial bedrock valleys or along modern streams and rivers. They occur at depths of up to 150 meters and are commonly separated from shallower aquifers by layers of less permeable diamicton (i.e., materials consisting of mixtures of gravel, sand, silt, or clay) or fine-grained lacustrine (lake) deposits. The distribution of major bedrock aquifers within 90 meters of ground surface in Illinois is shown in figure 3. Bedrock aquifers within 90 meters of ground surface cover most of northern and central Illinois and often are overlain by less permeable silts and clays. However, many are directly overlain by major sand and gravel aquifers, allowing direct hydrologic communication with shallower aquifer systems.

A site for HW or LLRW disposal should not necessarily be excluded from consideration if aquifers occur below a depth of 90 meters. However, the aquifers should be mapped, particularly if greater depth-to-aquifer considerations are warranted. In Illinois, major bedrock aquifers at depths greater than 90 meters are typically overlain by one or more layers of less permeable geologic materials (e.g., shales or fine-grained diamicton).

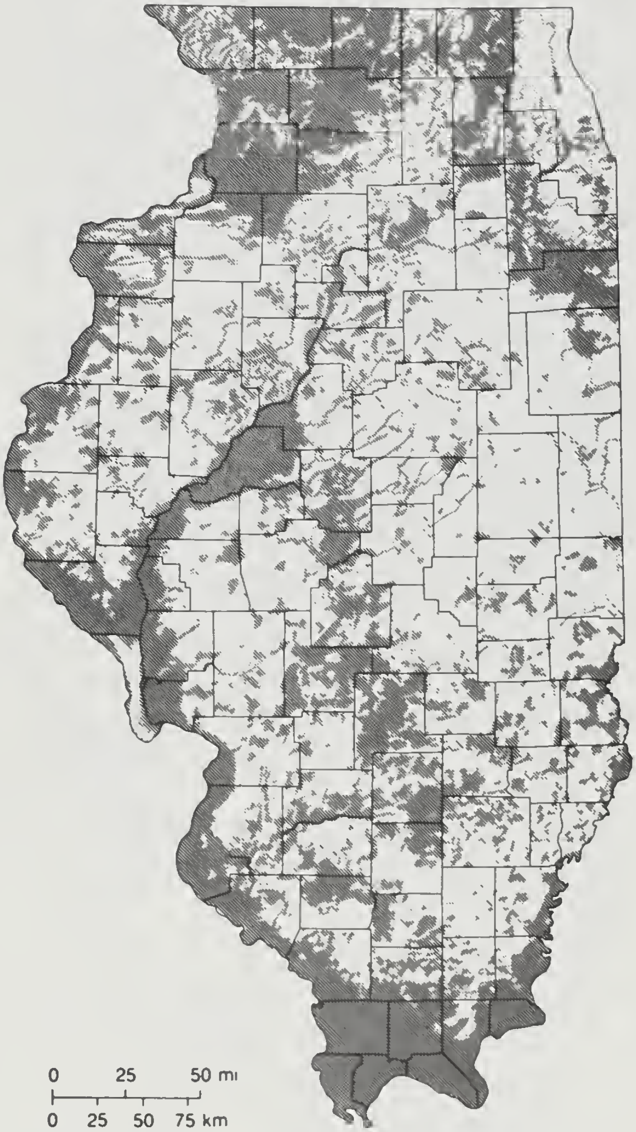


Figure 1 Aquifers within 15 meters of ground surface. Note: Aquifer materials are defined as sand and gravel units at least 1.5 m thick, sandstone at least 3 m thick, and fractured limestone or dolomite at least 4.5 m thick where water contains less than 2,500 mg/L of total dissolved solids (modified from Berg and Kempton, 1984).

A composite statewide map that shows the distribution of aquifers and other highly permeable materials within 15 meters of the surface, major sand and gravel aquifers at any depth, and major bedrock aquifers within 90 meters of the surface is shown in figure 4. Regions in the state that are not underlain by highly permeable materials within 90 meters of the surface, according to available maps, are mainly in central Illinois and restricted portions of northern Illinois.

The susceptibility of a geologic unit to contamination depends largely on the hydraulic characteristics (e.g., hydraulic conductivity and effective porosity) and thickness (depth to uppermost aquifer) of overlying geologic materials. The thicker and less conductive the overlying materials, the less susceptible underlying units are to contamination. In Illinois, sites containing thick sequences of unfractured fine-grained diamictons, shale, and dense limestone or dolomite offer the best potential for containing HW or LLRW and protecting underlying, more permeable formations. Hughes et al. (1971), in studying the average rate of groundwater flow through these fine-grained and relatively dense materials at landfills in northeastern Illinois, determined hydraulic conductivities for these materials on the order of 1×10^{-7} cm/sec. Deposits such as sand and gravel, sandstone, and fractured limestone and dolomite, all of which may be considered aquifer materials, commonly exhibit hydraulic

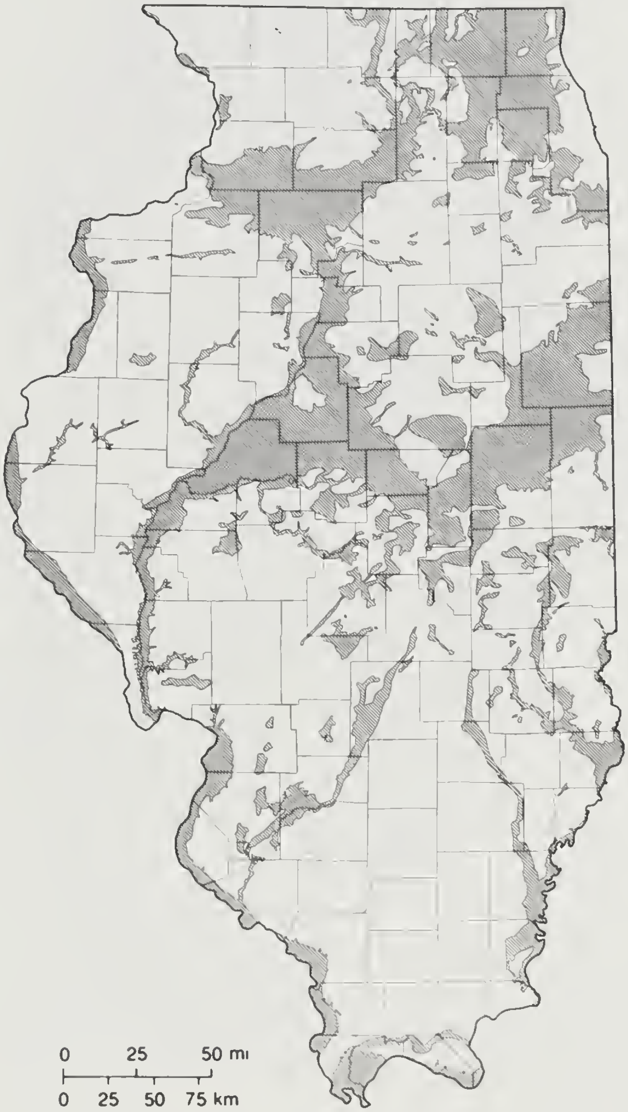


Figure 2 Major sand and gravel aquifers where water contains less than 2,500 mg/L total dissolved solids. (Data from: Berg and Kempton, 1984; Bergstrom and Zeizel, 1957; Bergstrom and others, 1968; Pryor, 1956; Selkregg and Kempton, 1958; Selkregg and Kempton, 1957.)

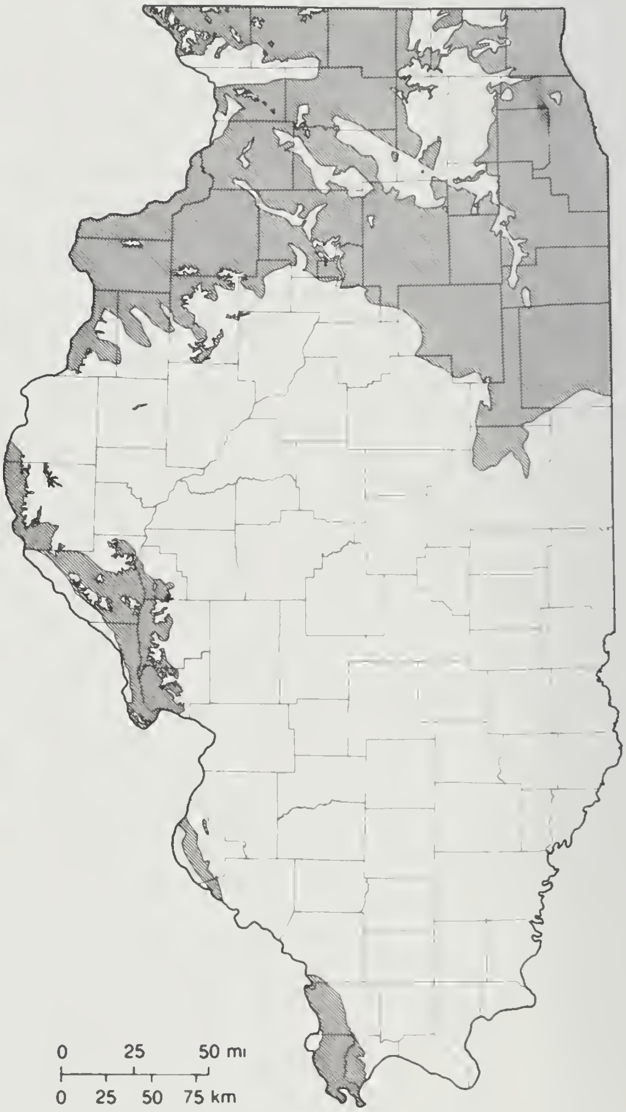


Figure 3 Major bedrock aquifers within 90 meters of ground surface where water contains less than 2,500 mg/L total dissolved solids. (Data from: Berg and Kempton, 1984; Bergstrom and Zeizel, 1957; Bergstrom and others, 1968; Pryor, 1956; Selkregg and Kempton, 1958; Selkregg and Kempton, 1957.)

conductivities of 1 x 10^{-4} cm/sec or greater (Berg, Kempton, and Stecyk, 1984b).

Disposal of LLRW should be avoided where permeable materials are continuous and the estimated travel time for contaminants to migrate from the facility to an accessible environment is less than 500 years. This 500-year period is the period of radiological hazard of the "average" low-level radioactive waste as defined by Siefken et al. (1982). Siefken et al. stressed that long groundwater flow paths from a facility to an accessible environment would allow LLRW to decay and disperse so as not to be hazardous. We recommend that a HW or LLRW disposal facility not be located within a region where high-conductivity materials (>1 x 10^{-4} cm/sec) are within 90 meters of the surface. Thick sequences of unfractured, fine-grained diamictons and dense limestone or dolomite should be considered potentially acceptable materials for either HW or LLRW disposal.

The 90-meter parameter is herein used only for regional mapping purposes. It represents the distance over which groundwater will flow in 500 years assuming that intervening materials have (1) an *in situ* hydraulic conductivity of at least 1 x 10^{-7} cm/sec, (2) an effective porosity of 10%, and (3) a hydraulic gradient of 0.6, and that no dilution, dispersion, and adsorption of potential contaminants occurs. Where permeable materials occur at depths greater than 90 meters, they are typically overlain by one or more aquitards (materials of low hydraulic conductivity that retard the movement of water and, presumably, contaminants); therefore, it is likely (but not certain) that any contaminant released from a waste disposal facility will decay, disperse, be adsorbed, or be diluted prior to reaching these deeper permeable materials (Cartwright, Miller, and Berg, 1986).

RECHARGE AREAS

Recharge is the movement of groundwater downward from the ground surface toward an aquifer. Upland areas consisting of coarse glacial deposits or shallow fractured bedrock are areas of high recharge. Though no simple relationship exists between groundwater recharge and groundwater discharge, large discharge rates tend to coincide with large recharge rates because of the presence in upland areas of surficial permeable materials (sand and gravel or shallow, fractured bedrock). Similarly, groundwater recharge and discharge rates are comparatively smaller for low-lying areas containing fine-grained surficial sediments or shallow, impermeable bedrock. Because high recharge areas are often associated with shallow aquifers (less than 15 meters deep), potential aquifers, or other highly permeable materials, such areas should be excluded from HW or LLRW disposal.

Recharge conditions and rates for several aquifers in Illinois were described by Walton (1965). Groundwater discharge rates for various climatic and regional conditions in Illinois were described by Walton (1965) and more recently by Gibb and O'Hearn (1980).

REGIONAL GROUNDWATER FLOW

Shallow groundwater movement is generally controlled by the topography of the land surface and the type of geologic material present. Estimates of the regional groundwater flow direction often can be determined even where available groundwater information is sparse. Groundwater generally moves from topographically high areas, where recharge occurs, to topographically low areas, where groundwater discharges to lakes, perennial streams, and wetlands. Topographic maps are useful for reviewing the location and distribution of surface features to determine the general direction of regional shallow groundwater movement. A nearby discharge area could represent the point of contaminant release from the groundwater system to surface water.

HW or LLRW disposal should be avoided in areas where regional groundwater flow data suggest a high potential for contamination of an aquifer or surface-

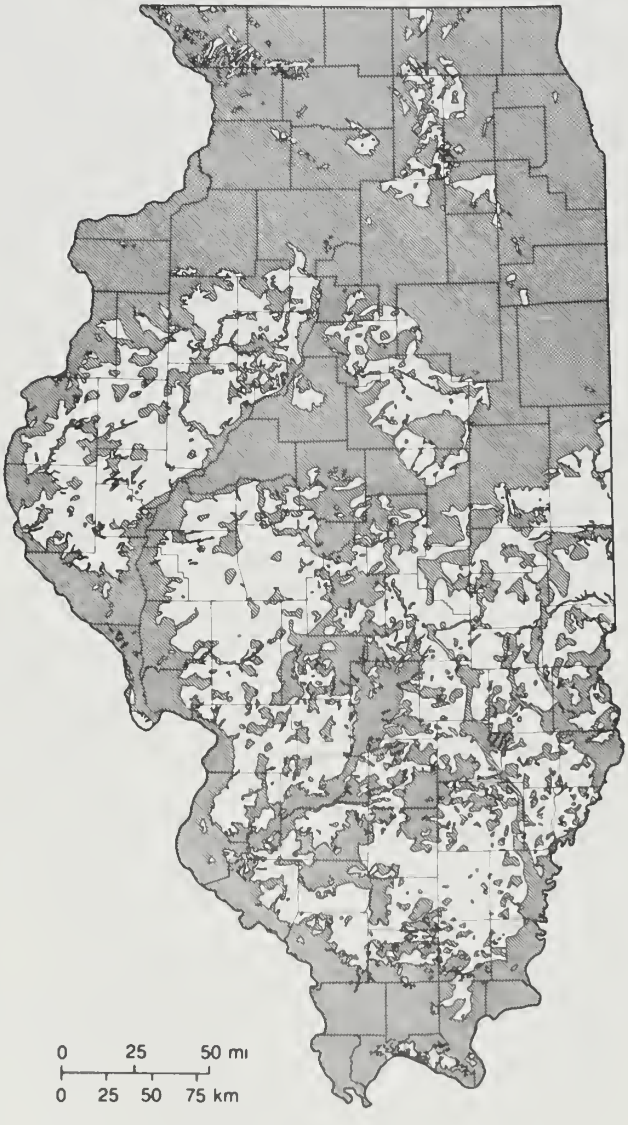


Figure 4 Composite map of aquifers in Illinois.

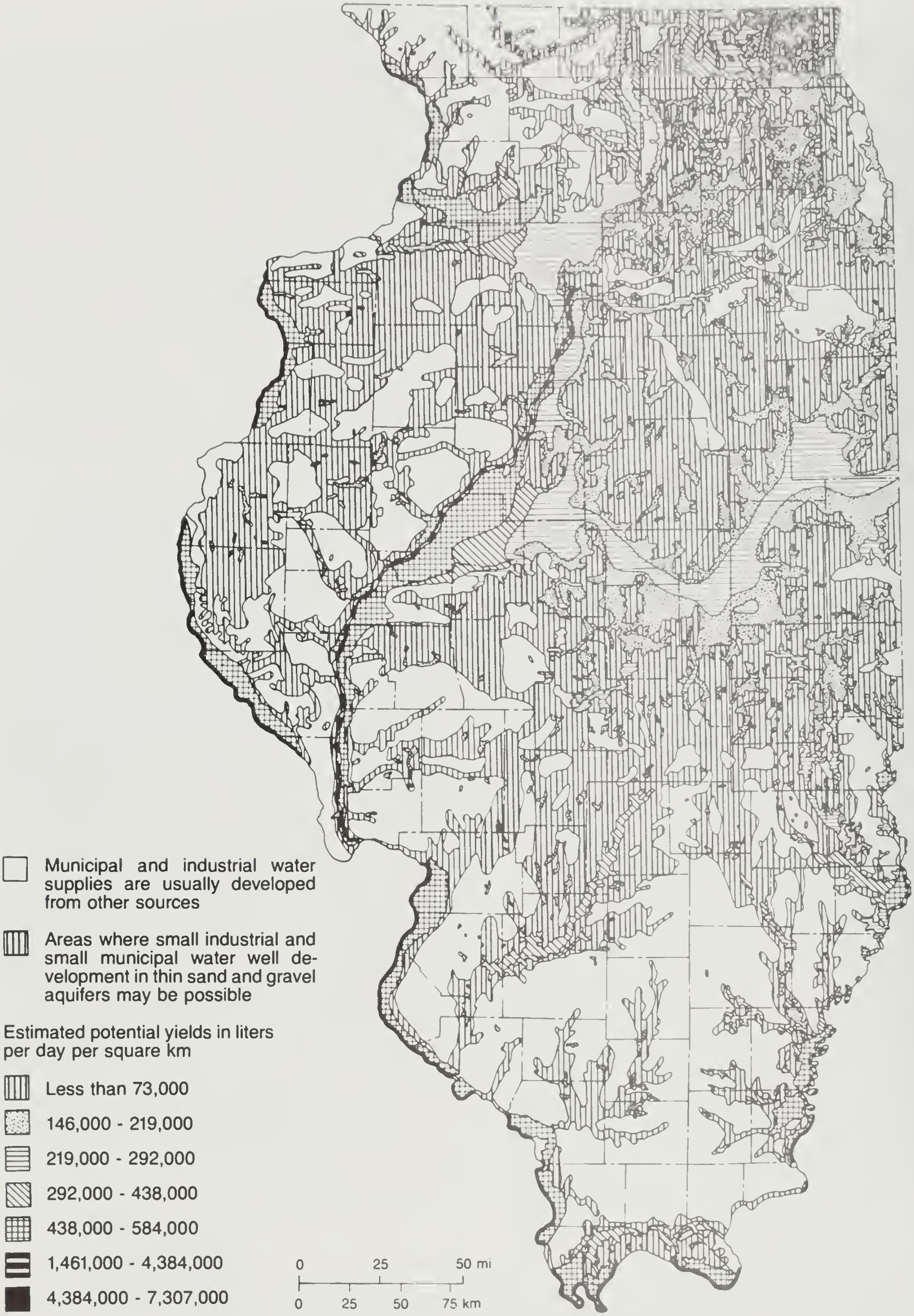


Figure 5 Estimated potential yields of principal sand and gravel aquifers (Illinois Technical Advisory Committee on Water Resources, 1967.)

water body. However, the hydrological suitability of a site should be determined through site-specific investigations and modeling.

WELL YIELD/POTENTIAL AQUIFER YIELD

Areas overlying aquifers of high potential yield represent areas likely to be developed for major groundwater withdrawals. Such areas may also have significant recharge capacities, generally reflecting hydrogeological conditions sensitive to contamination from surface and near-surface activities. High-yielding wells in an area are indicative of an aquifer with high potential yield. Estimated potential yields of principal sand and gravel aquifers in Illinois are shown in figure 5.

The yield of a well is the quantity of groundwater that may be obtained from an aquifer, expressed usually in liters per minute (Lpm) or liters per day (Lpd). Potential aquifer yield is the long-term sustainable quantity of water that can be withdrawn from a hydrogeologic unit, usually expressed in liters per day per square kilometer of aquifer area (Lpd/sq km). Aquifer yield should not exceed average annual recharge.

Well yields may be generally classified as follows (Illinois Department of Energy and Natural Resources, 1984):

- Low—yields of 40 Lpm or less
- Moderate—yields ranging from 40 to 400 Lpm
- High—yields greater than 400 Lpm

Potential aquifer yields similarly may be classified:

- Low—potential yields below 73,000 Lpd/sq km.
- Moderate—potential yields between 73,000 and 146,000 Lpd/sq km
- High—yields greater than 146,000 Lpd/sq km

As stated previously, HW or LLRW disposal facilities should be sited away from any aquifer or other highly permeable materials delineated on regional maps as occurring within 90 meters of land surface. Some low potential-yield aquifers that occur locally will have to be evaluated as part of the area-screening and site-characterization steps of the siting program.

GROUNDWATER QUALITY

The quality of the groundwater must be well known before siting a HW or LLRW disposal facility. Groundwater quality is defined by the chemical constituents in the water, including particulate and dissolved matter, immiscible liquids, and microbiological organisms. Groundwater quality data are helpful for determining the usefulness of groundwater as a potable resource. These data also provide background information that can be used during monitoring programs established before, during, and after facility operation.

Regional groundwater quality should be evaluated for its potential effects on hazardous or radionuclide contaminant transport, as well as for its potential for hampering (masking) contaminant detection. Certain groundwater characteristics may enhance leachate mobility. In particular, metal ion solubility and mobility is much greater under low pH conditions (Matthess, 1982). Complexation processes may enhance the mobility of metals, hazardous substances, and radionuclides (Broadbent and Ott, 1957; Duguid, 1975; Killey et al., 1984). Other characteristics may slow contaminant migration by causing dissolved waste constituents to precipitate or adsorb to geologic materials (Griffin et al., 1976; Matthess, 1982). Where known, factors that may suggest groundwater age, such as ^{14}C and H_3O, can give an indication of the rate of groundwater recharge.

Poor regional groundwater quality may be sought during screening as a means to minimize conflicts often associated with siting near usable groundwater. Generally, areas containing nonpotable groundwater would be preferred for waste disposal over areas where the quality of groundwater resources is good. However, water quality that has been degraded by the operation of other nearby activities may interfere with efforts to detect off-site contaminant migration. The commingling of contaminant plumes can greatly increase the difficulty of determining contaminant sources, particularly when the contaminants are chemically similar. In addition, areas where groundwater quality has been degraded by man-made causes should be avoided because this resource may eventually improve.

REGIONAL KARST FEATURES

Karst landscapes are those that have undergone modification from the dissolution of underlying carbonate rocks, such as limestone, dolomite, and gypsum. Underground caves, sinkholes, and "lost rivers" are a few of the features that characterize a karst terrain. Land subsidence and often very rapid groundwater flow characterize karst regions. Karst terrain should be avoided in the siting of a HW or LLRW disposal facility because of the unpredictable nature of groundwater movement in these areas and the unstable nature of landforms. Regional karst features in Illinois have been mapped by Bretz (1961) and are shown in figure 6.

REGIONS OF UNDERMINED AREAS

Subsidence of the land surface can occur in regions that have been undermined, and such regions should be noted during regional screening. Subsidence can alter water and contaminant flow patterns and damage containment facilities. However, current hydrogeological studies by the Illinois Mine Subsidence Research Program show that, except for the immediate collapse zone above a mine, hydrological characteristics of the overburden remain unaffected.

The degree and risk of subsidence depends in part on the extensiveness of the mining and the nature of the mining process. In some areas, subsidence already has occurred, thus reducing the potential for additional collapse. Areas that have been undermined should be evaluated for HW and LLRW disposal on a site-by-site basis. Disposal facilities located in these areas should be designed for possible subsidence.

Detailed descriptions of land subsidence due to underground mining in Illinois are presented by DuMontelle et al. (1981), Hunt (1980), and Illinois State Geological Survey (1980). In Illinois, the principal mineral extracted from underground mines has been coal (figure 7).

REGIONS OF SEISMIC RISK

Seismic risk refers to the potential damage from future earthquakes. Seismic risk is usually determined from historical seismic activity, known zones of weakness in the earth's crust, and the nature of surficial materials in a given region. Seismic risk applies primarily to artificial structures but also can be applied to geologic materials.

HW or LLRW disposal facilities should be designed to be extremely stable structures. A seismic risk assessment should address whether ground shaking at the selected site may (1) damage or rupture containment structures, (2) alter the flow of groundwater and surface water at the site, (3) interrupt site access and hamper proper site maintenance and operation, and (4) promote mass movements of materials through subsidence, slumping, and landsliding. Changed patterns in groundwater flow also could affect previously determined paths of contaminant migration. Altered surface-water flow could result in increased erosion and possible exposure of contaminants.

Figure 8 is an earthquake intensity map of the midwestern United States based on a seismic event of 7.1 to 7.4 on the Richter Scale. During the winter of 1811-12, a sequence of earthquakes with body wave magnitudes of 7.2, 7.1, and 7.4 did occur in this region,

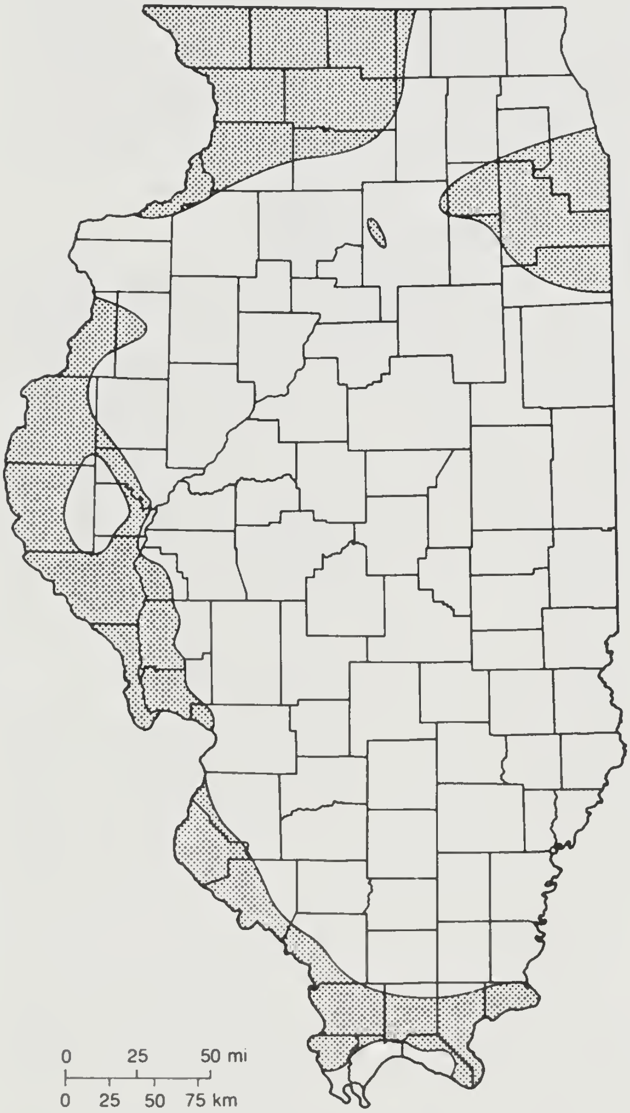


Figure 6 Areas where limestone or dolomite are at or near the surface. These are potential karst areas (Bretz, 1961).

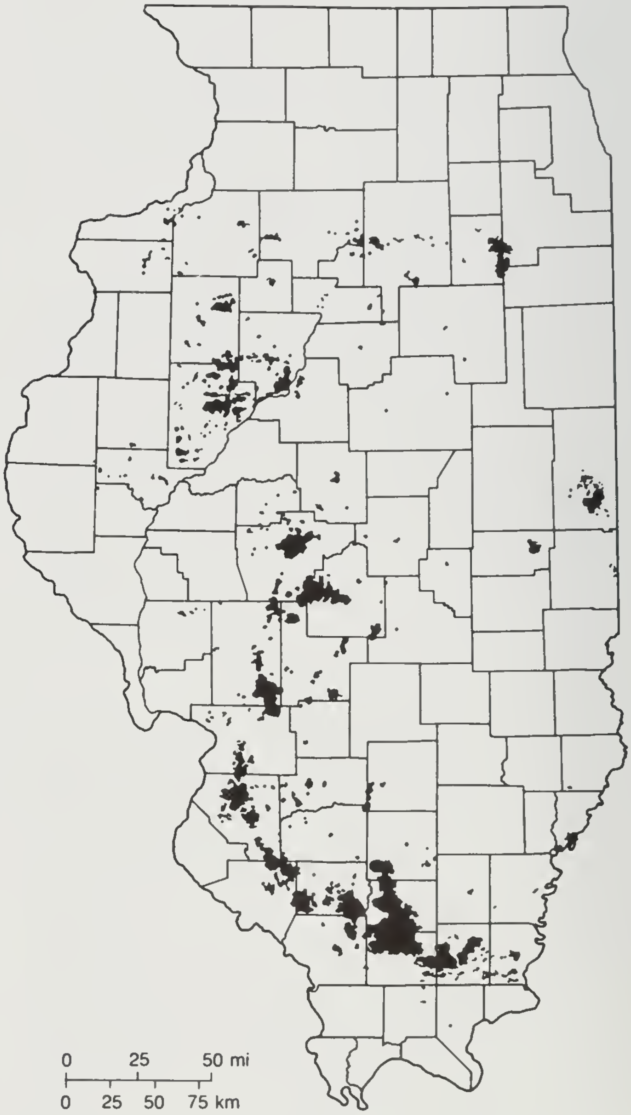
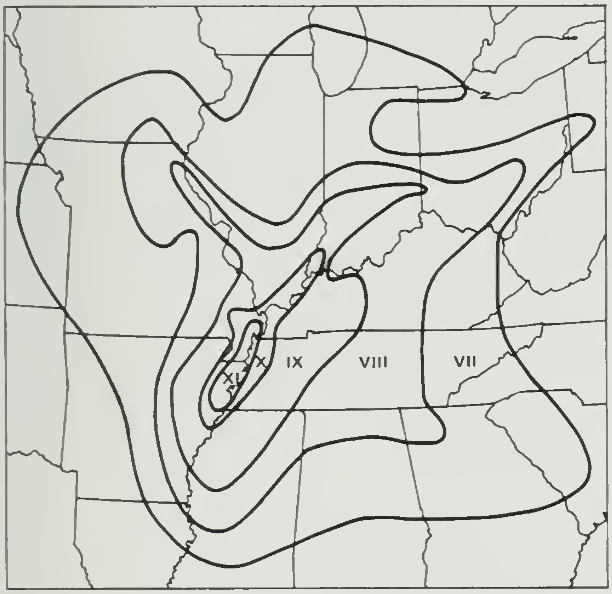


Figure 7 Areas of Illinois undermined for coal (DuMontelle, et al., 1981).

epicentered near New Madrid, Missouri. Intensities on this map are based on the Modified Mercalli Intensity Scale of 1931 (Holmes, 1965) and are highly generalized because actual damage is also related to the surficial geologic material. On the Modified Mercalli Intensity Scale, a value of VIII or greater is usually associated with damage to poorly constructed manmade structures.

No active faults, i.e., faults that have offset materials deposited during the Quaternary period (the past 1 to 2 million years), have been discovered in Illinois. However, some steeply sloping regions could be affected by seismic activity epicentered in Illinois or adjacent states. The intensity distribution of a New Madrid-type of seismic event shows intensities as high as X in extreme southern Illinois and as high as VIII over the southern third of the state.

Because there has never been an historical earthquake epicentered in Illinois with maximum intensity greater than VII on the Modified Mercalli Intensity Scale, the greatest seismic risk in Illinois is associated with a repeat of a New Madrid-type seismic event (figure 9). Therefore, we recommend that any HW or LLRW disposal facility sited for areas shown as intensity X in figure 8 should be suitably designed to withstand seismic activity of this magnitude. Sites should be avoided on soils that are very sensitive to the effects of seismic activity (for example, subject to liquefaction), or additional design efforts may be necessary to make the disposal facility "earthquake proof."



VII	Very strong	general alarm; walls crack; plaster falls
VIII	Destructive	masonry cracks; chimneys fall; poorly constructed buildings damaged; water well levels may change
IX	Ruinous	some houses collapse where ground begins to crack; pipes break open
X	Disastrous	ground cracks badly; many buildings destroyed and railway lines bent; landslides on steep slopes
XI	Very disastrous	few buildings remain standing; bridges destroyed; all services (railway, pipes, and cables) out of action; great landslides and floods

Figure 8 Map showing earthquake intensity in the midwestern United States that would result from a seismic event comparable to the New Madrid sequence of 1811-1812. Note that this map is generalized (Hopper, Algermissen, and Dobrovolny, 1983).

Figure 9 Seismic risk map for Illinois. The map divides Illinois into three zones: Zone 1, expected minor damage; Zone 2, expected moderate damage; Zone 3, where major destructive earthquakes occur (modified from Algermissen, 1969).

AREA SCREENING

INTRODUCTION

The regional directive screening process identifies those regions with the greatest potential for HW or LLRW disposal. Based upon this information, candidate sites in favorable regions can be selected. Prior to an exploratory drilling program that characterizes a site in detail, area screening should be performed at, and in the vicinity of, each candidate site. This additional screening may detect potential geologic, hydrologic, or geomorphic features that did not show up on regional maps because of their small scale or because the features were previously unknown. The presence of some of these conditions may seriously limit or exclude a site from consideration for HW or LLRW disposal. The presence of other conditions may significantly increase the cost of site exploration and groundwater modeling programs or increase the cost of engineering design to offset a potential hazard.

By using available surficial and subsurface data for the immediate geographic area, the area-screening process more accurately delineates geological and hydrological conditions determined during regional screening. This process may involve a reinterpretation of existing maps. Available water-well data, engineering tests, boring logs, and published and unpublished geological and hydrological reports for the immediate area and the region should be procured. Particular caution, however, should be used in evaluating some of these data. Boring logs often contain misleading information and/or lack the information necessary to properly analyze a particular condition. It is imperative that sample sets or descriptions and evaluations of materials by geologists accompany log data. In Illinois, the study of Boone and Winnebago Counties by Berg, Kempton, and Stecyk (1984b) is an example of the range of data needed.

Studies conducted by the U.S. Geological Survey, local health and planning agencies, and consultants should be used, especially for determining the regional hydrologic suitability of an area for disposal. In Illinois, review of available reports and files at the ISWS and ISGS will provide considerable information in regard to these data needs. A brief summary of the types of information contained in these files is provided in table 3.

The following elements should be evaluated as part of the area-screening process:

- Site topography/slope stability
- Area geological framework and aquifer mapping
- Well inventory

Table 3. Summary of ISWS and ISGS groundwater files.

File name	How filed	Contents of file
Basic Data (ISWS, ISGS)	By county, then legal location (Section, Township, Range)	Private well records (logs), private water quality analyses
Reports (ISWS, ISGS)	Same as Basic Data	Correspondence and short letter-reports summarizing basic data primarily on groundwater availability for private users. Also, site suitability evaluations, generally for waste-handling operations (e.g., landfills, treatment lagoons).
Municipal (ISWS)	By county, then alphabetically by municipality name. Follows Basic Data and Reports Files	All types of historical information regarding municipal water supply. Correspondence, reports, well records, pumpage, Illinois Environmental Protection Agency (IEPA) inspection reports, water quality analyses, well/aquifer test data. Also, may include industrial well records if industry is located in town.
Original Well Test (ISWS)	By county, then by owner in alphabetical order	Original field data sheets and analyses of well and aquifer tests conducted by ISWS. Principally conducted on municipal and industrial wells. Calculated aquifer hydraulic properties, long-term aquifer or well yields.

- Groundwater withdrawals
- Strongly weathered materials
- Inactive fault zones
- Material fracturing
- Material engineering properties
- Local karst features
- Mineral resources
- Mined areas

SITE TOPOGRAPHY/SLOPE STABILITY

To avoid potential slope erosion and stability problems, topographic and soil maps can be examined to locate a site in a relatively flat upland terrain away from surrounding higher upland areas and major groundwater discharge zones. Information on slopes can be obtained from topographic maps or from county soil survey maps available from the U.S. Department of Agriculture, Soil Conservation Service. A more detailed discussion of site topography and slope stability is presented in the site-characterization section of this report.

The susceptibility of terrains to mass movements near a candidate site should be determined and used as a criterion in identifying potentially suitable regions for HW or LLRW disposal. Candidate sites near landforms that exhibit numerous slope failures or contain geologic materials prone to mass movements should be excluded from HW or LLRW disposal. Studies to evaluate terrain susceptibility should include the following three procedures: (1) a literature review of documents pertaining to mass movement susceptibility in areas of interest, (2) examination of cartographic data such as topographic, geologic, and soil maps, and (3) remote sensing techniques (Way, 1978), particularly aerial photographs.

Previously prepared documents usually identify earth materials or sequences of materials that are prone to slope failure and the type (e.g., slide, flow, or heave) and mechanisms of failure. Pertinent reports that discuss terrain susceptibility to mass movements in Illinois include DuMontelle et al. (1971), Ekblaw (1929, 1954) and Krumm (1984). Of particular interest is a report by Killey, Hines, and DuMontelle (1985), which includes a map (scale 1:500,000) showing the types and locations of known landslides and landslide-prone areas in Illinois.

Remote sensing techniques, coupled with preliminary field reconnaissance and particularly large-scale aerial photography, are probably the most effective methods for delineating the distribution and extent of mass movements. Remote sensing techniques should also be used to identify vulnerable locations of slope failure, such as cliffs, banks, or steep slopes undercut by stream or wave action, areas of concentrated drainage or seepage, and areas of hummocky (irregular and rugged) ground. Information pertaining to the use of remote sensing and aerial photographic techniques may be obtained from Colwell (1983); Miller (1961); Norman, Liebowitz, and Fookes (1975); Rib and Liang (1978); and van Zurdam (1986).

Mass movements also may be identified by studying their surficial morphologic expression on topographic maps. Landslides (and some types of flows) are commonly characterized by closely spaced contours (indicating a steep slope at the head of a slide) and an irregular nonsymmetrical contour pattern with shallow depressions downslope in the slide mass (Rib and Liang, 1978). Wavy contour lines or offset roads, transmission lines, or other lineaments also may indicate mass movements. All areas of potential slope failure should be checked during field reconnaissance and with aerial photography.

Information from the literature review, cartographic data, and remote sensing techniques should be combined with maps showing the distribution and sequence of earth materials near ground surface and then used to determine sequences of geologic materials prone to mass movements. Regional earth material maps in Illinois, for example, include: (1) Quaternary Deposits of Illinois (Lineback, 1979), showing the distribution of Quaternary deposits at ground surface, (2) the Geologic Map of Illinois (Willman et al., 1967), which illustrates the distribution of bedrock at ground surface and immediately beneath the Quaternary deposits, and (3) the Stack-Unit Map of Illinois (Berg and Kempton, 1988), which shows the distribution and sequence of geologic materials to a depth of 15 meters. Additional information may be obtained from the General Soil Map of Illinois (Alexander et al., 1984), which illustrates the distribution of soil associations in the state, and from Killey, Hines, and DuMontelle (1985).

GEOLOGICAL FRAMEWORK AND AQUIFER MAPPING

The area geological framework showing the depth, distribution, and thickness of aquifers or continuous highly permeable materials at and near a candidate site must be determined. Such information is needed to confirm or reject previously gathered regional geological data on estimated travel time to an aquifer, potential aquifer, or other material with high contaminant transmitting capabilities. Travel time must be long enough so as not to allow contaminants to reach a groundwater resource. This is determined in a manner similar to that used during regional directive screening. Although anything less than a 500-year groundwater travel time may warrant exclusion of a LLRW regional site from consideration (Berg et al., 1989b), hazardous wastes at health-risk levels may persist in the groundwater environment much longer than 500 years. Therefore, groundwater travel time evaluation can only be determined on a site-specific basis and only if the geohydrologic environment is well known.

Water-well and engineering test boring records and other available data (e.g., subsurface geophysical surveys) should be obtained to determine the presence of subsurface materials of high hydraulic conductivity (on the order of 1×10^{-4} cm/sec or greater) within 90 meters of the surface. This screening should be verified by sample studies as prescribed by Landon and Kempton (1971).

If the data indicate that continuous horizons of permeable materials are present at the proposed site and in the area immediately surrounding the site, then the site probably should be excluded from consideration for waste disposal. The presence of discontinuous horizons of permeable materials, often with low-yielding capabilities, also may warrant exclusion of the site. A detailed drilling program during site characterization ultimately must determine whether the subsurface permeable horizons are indeed discontinuous and do not compromise site suitability. In addition, site-specific modeling of potential contaminant transport also may indicate that travel times do not pose a serious threat to groundwater resources.

WELL INVENTORY

The first and probably easiest hydrological task to accomplish during area screening is a well inventory. This will aid in establishing the groundwater flow system in the vicinity of the candidate site. A well inventory should be conducted within a 10-kilometer radius of the site and should include a well-record compilation from available files and a door-to-door field survey. It is imperative that as much information as possible be gathered from well records, conversations with well owners (and drillers), and field reconnaissance. A preliminary screening is usually accomplished by reviewing available records, followed by the field survey.

Well inventories generally include information on the well location, well depth, and amount of water withdrawn. Well locations, along with a depth notation, should be plotted on a map of the study area. The well inventory should include the manner in which the water is used (e.g., domestic or municipal supply, irrigation, livestock watering, food or industrial processing, or cooling). It also should include information on how each well was constructed: whether it was drilled, bored, or hand-dug; whether it was cased and grouted, bricked, tiled, screened and gravel-packed, or drilled to rock and then left as an open borehole; and to what depths the casing, screen, gravel-pack, and annular seals were placed. The geologic formation or formations producing the water also should be noted.

Where available, static and pumping water-level information, both current and historical, should be collected to establish groundwater flow direction and responses to pumpage. Well or aquifer test information conducted on wells within the study area or wells within the same aquifer provide information necessary for determining aquifer hydraulic properties.

Water samples should be collected during field reconnaissance. The depth interval and the pumping conditions under which each sample is collected should be noted. Changes in water chemistry also should be noted and explained. When the hydrogeological investigations are complete, the nearest downgradient users and municipal supplies should be identified on a base map. Areas with large numbers of wells indicate the likely presence of a viable groundwater resource; candidate sites should be excluded from these areas.

GROUNDWATER WITHDRAWAL

Points of groundwater withdrawal (i.e., public and private wells, including industrial and irrigation wells) should be located at a sufficient distance from a disposal site to avoid possible contamination should a contaminant release occur. This approach minimizes the likelihood of contamination of a well and, in case the aquifer becomes contaminated, maximizes the opportunity for contaminant plume attenuation between the contaminant source and the well. It also increases the time available for implementing mitigation.

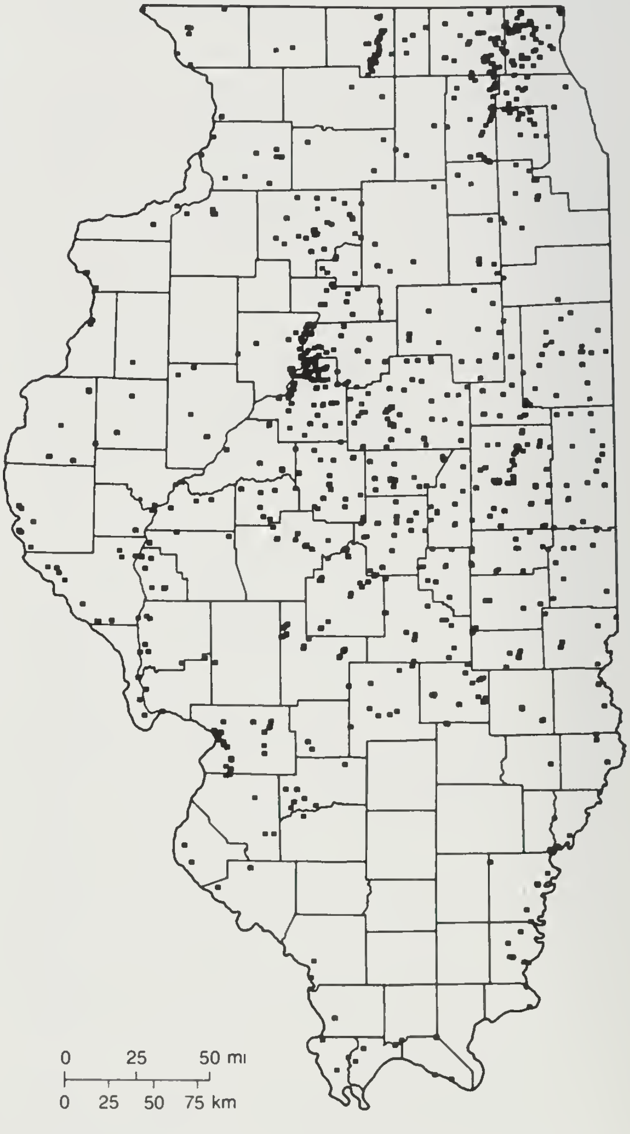


Figure 10 Public water supply wells tapping sand and gravel aquifers (PICS Database, ISWS, 1989).

The location of municipalities should be mapped. Major groundwater withdrawals influence the direction of groundwater movement. Public, agricultural, and industrial water supply wells in and around municipalities may withdraw enough water to significantly influence groundwater movement at or near a candidate site. Pumpage and groundwater level records, where available, should be used to determine the effect a well or well field may have on groundwater movement. Wells constructed to similar depths, or the use of one aquifer or a group of aquifers, may signify the existence of a regional or local groundwater resource. Information on the extent and use of such resources should be determined. The locations of municipal wells tapping sand and gravel, shallow bedrock, and deep bedrock aquifers in Illinois are shown in figures 10, 11, and 12. In addition to municipal water supply wells, all private domestic, industrial, and irrigation wells in the area, inventoried during a field survey, should be mapped and estimates made on the amounts of water withdrawal.

PRESENCE OF STRONGLY WEATHERED MATERIALS

Stratigraphic information, including relative and absolute ages of depositional units, should be obtained to determine the potential presence of materials that are strongly weathered (a more detailed discussion of weathering is presented in the site-characterization section of this report). Fractures resulting from soil formation may provide pathways of contaminant migration. Although this condition exists over much of the Midwest, degrees of weathering intensity and soil preservation vary. In Illinois, the greatest potential for

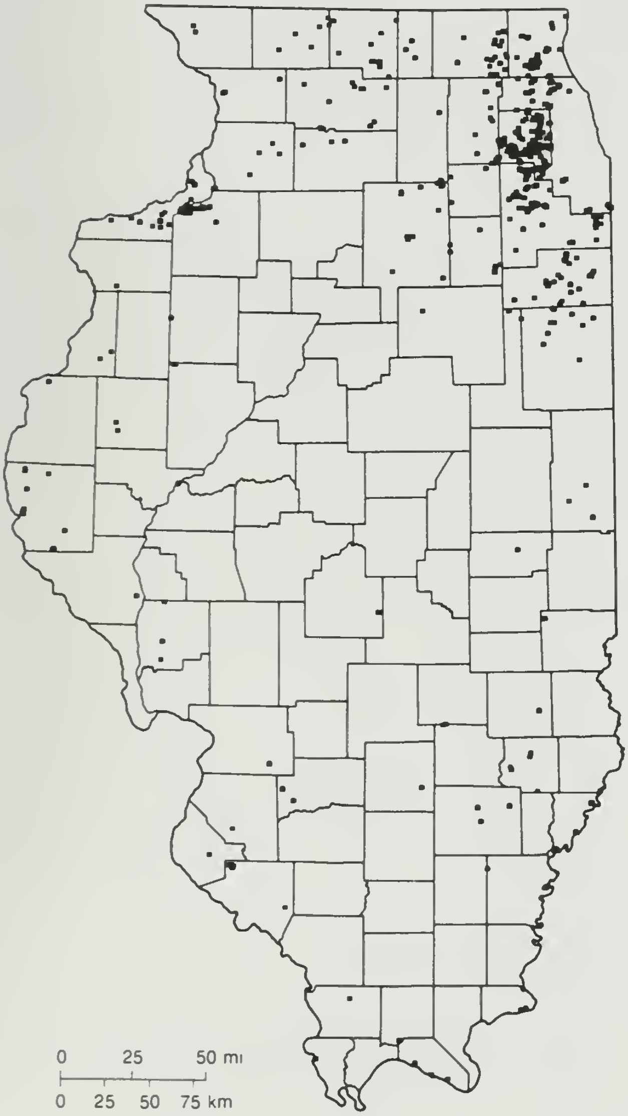


Figure 11 Public water supply wells tapping shallow bedrock aquifers (PICS Database, ISWS, 1989).

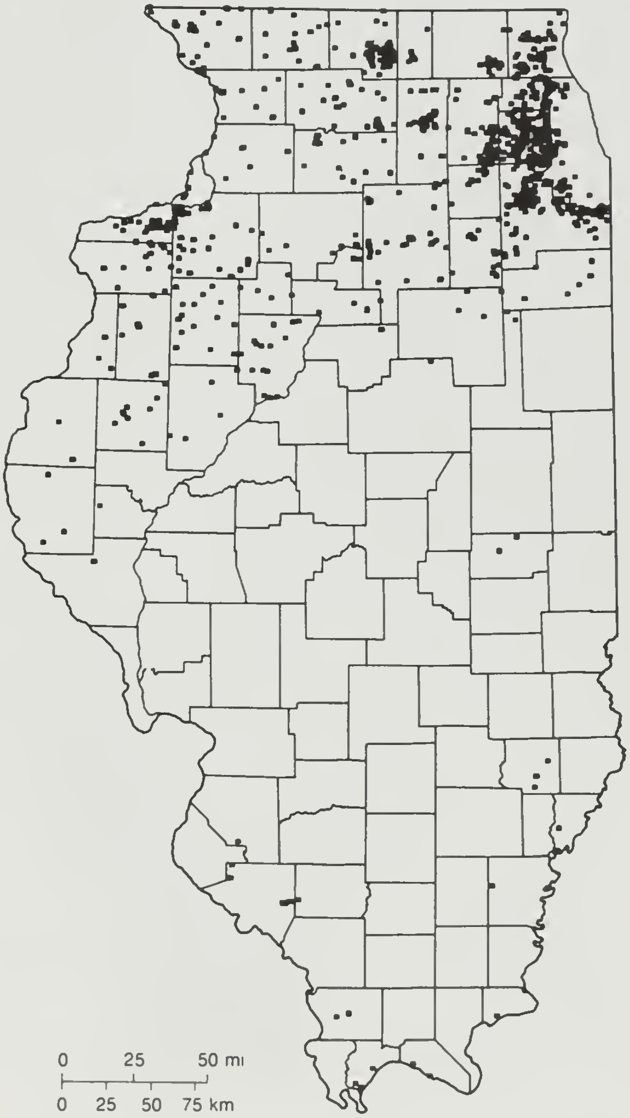


Figure 12 Public water supply wells tapping deep bedrock aquifers (PICS Database, ISWS, 1989).

problems that may affect site performance would occur in areas where the Sangamon Soil occurs within 10 meters of the surface (figure 13).

Only in certain regions will existing local stratigraphic information be sufficient to warrant exclusion of a site on the basis of weathering of materials. The determination of weathering and exclusion of a site on the basis of extreme weathering is best done in conjunction with the drilling program during site characterization.

FAULT ZONES

Fault zones are regions containing materials that have been displaced (Hobbs, Means, and Williams, 1976). They therefore may present difficulties in hydrological and geological characterization. Severe disruption of a waste disposal facility could obviously result in areas of active faults. Inactive faults, as defined by the USNRC, have been inactive for at least 10,000 years. In certain situations, inactive faults may provide barriers to the movement of groundwater due to the displacement of highly permeable beds. However, in most cases, regions of extensive inactive faults would be unsuitable for HW or LLRW disposal. These regions may provide (1) avenues for potential migration of hazardous waste or radionuclides from a disposal facility, (2) increased infiltration of surface water and contaminants, (3) interaquifer exchange of contaminants, and (4) difficulties in predicting groundwater flow direction and rate. In addition, faults at or near the surface may channel water to a particular portion of the site, thereby increasing channelized flow and surficial erosion.

Figure 13 Surficial distribution of pre-Wisconsinan deposits and the Sangamon soil (from Willman and Frye, 1970).

We recommend that all candidate sites overlying an active fault or extensive inactive fault zones be excluded from consideration for HW or LLRW disposal. A site also should be excluded if it can be shown that potential contaminants could migrate from the site to a major fault zone. Travel time for radionuclides should be 500 years or longer, and for hazardous wastes, travel time should be for a sufficiently long period, as determined by licensing agencies.

Although active faults do not occur in Illinois, extensive inactive faults and fault systems occur in much of southern Illinois (figure 14). Detailed descriptions of these faulted regions are discussed by Braile et al. (1982); Bristol and Treworgy (1979); Heyl (1972); Keys and Nelson (1980); Kolata, Buschbach, and Treworgy (1978); Kolata, Treworgy, and Masters (1981); Krausse and Keys (1977); McCracken (1972); Nelson and Krausse (1981); Nelson and Lumm (1984, 1985); Treworgy (1981); and Wilcox, Harding, and Seely (1973).

FRACTURING OF GEOLOGIC MATERIALS

Geological information should be obtained by examining existing data on the potential of extensive fracturing of drift (fine-grained) and bedrock (i.e., shales, limestones, sandstones) at and near candidate sites. Specific geological reports may provide insight into existing conditions at a candidate site. However, determining that a site should be excluded from HW or LLRW disposal because of extensive fracturing of materials can be done adequately only during site characterization. Fracturing is discussed in more detail in the site-characterization section of this report.

ENGINEERING PROPERTIES OF GEOLOGIC MATERIALS

Geologic materials susceptible to collapse, shrinking, swelling, and liquefaction can be evaluated by determining the type of geologic materials at and near a candidate site. Candidate sites containing materials potentially susceptible to failure should be avoided. The exclusion of a site because of the presence of collapsible materials and those with high liquefaction

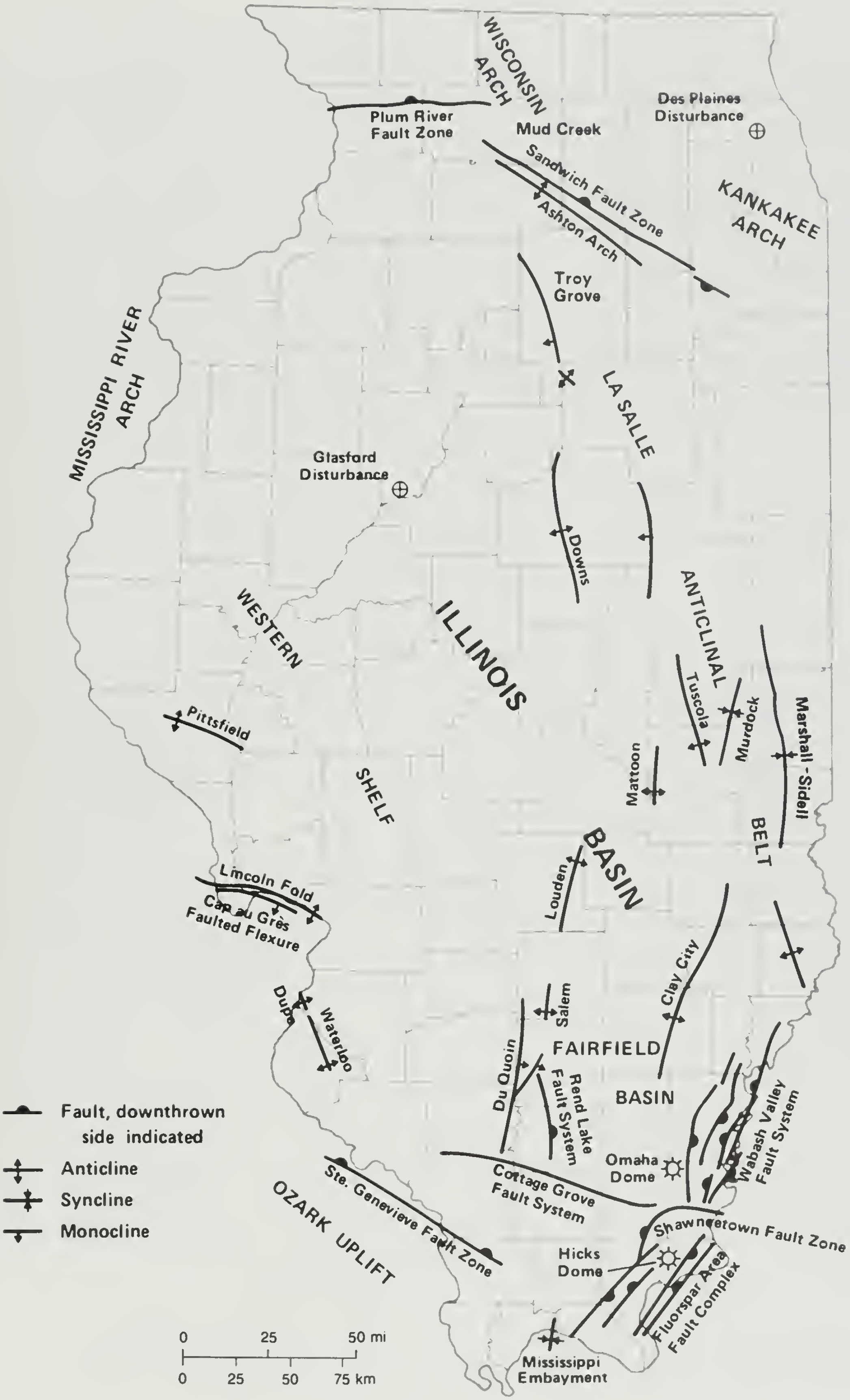


Figure 14 Major geologic structures of Illinois, including primary inactive fault zones (modified from Treworgy, 1981).

potential should be based only on the results of the site-characterization study. In Illinois, regional and local data on engineering properties of geologic materials are available at the ISGS and from engineering and geological consultants who have conducted investigations in the region of interest. A detailed description and specific recommendations regarding engineering properties are presented in the site-characterization section.

LOCAL KARST FEATURES

Area screening for karst features should be done by using aerial photographs and large-scale topographic maps. The presence of karst features affects potential site suitability. If karst features exist at a candidate site, the site probably should be excluded from consideration for HW or LLRW disposal. If karst features predominate in the region surrounding the site but do not exist within immediate site boundaries, determination for exclusion will have to be made during the drilling and site-characterization process.

MINERAL RESOURCES

The presence of recoverable mineral resources at or near a candidate site may not pose an immediate environmental hazard that would exclude a site from consideration for HW or LLRW disposal. However, the presence of a significant concentration of a mineral resource may greatly affect the long-term suitability of the site for waste disposal. Economic pressures and demand for a resource cannot be predicted over the waste containment period; currently unsought mineral resources may be needed in coming years. Future extraction, therefore, should be considered a possibil-

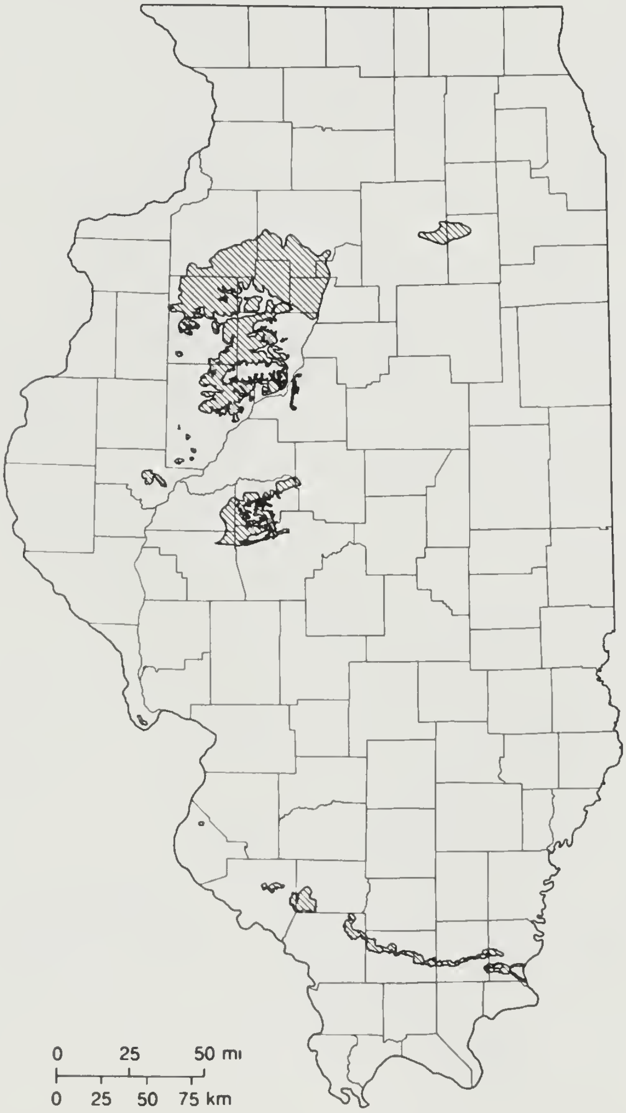


Figure 15A Strippable reserves of the Springfield (No. 5) Coal (modified from Smith and Stall, 1975).

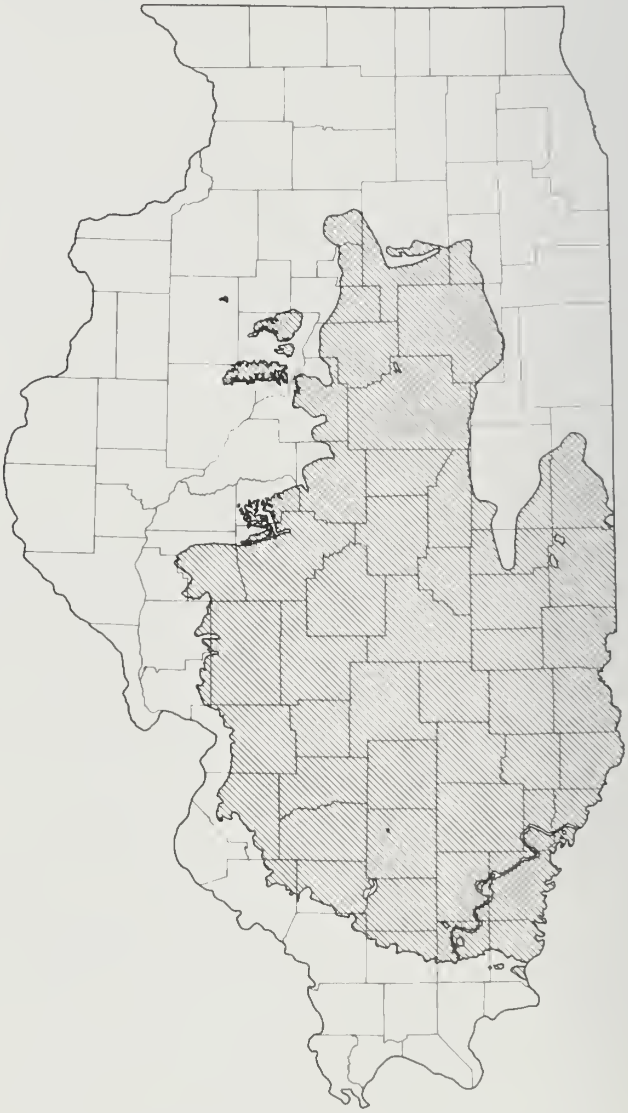


Figure 15B Deep resources of the Springfield (No. 5) Coal (modified from Smith and Stall, 1975).

ity. The process and consequences of extraction (including blasting and later subsidence) can affect the operations at a disposal facility and perhaps decrease its performance. Ramifications of locating a site near mined areas are discussed in the next section.

Economic feasibility studies should be conducted if a candidate site is located in an area containing a recoverable mineral resource. Because of the broad distribution of mineral resources in states such as Illinois (coal and limestone or dolomite underlie much of the state) avoidance of all potentially recoverable mineral resources may leave only unsuitable locations for siting HW or LLRW facilities. Therefore, we recommend that the potential use of any economically recoverable mineral resource be the principal consideration for siting rather than just the absolute distribution of the resource. Considerations must include (1) the availability of the resource for economic recovery (including depth to the resource), (2) resource quality, (3) resource quantity, and (4) most importantly, economic feasibility of resource exploitation, including consideration of the likelihood of an inadvertent intrusion into containment structures.

In Illinois, regions of mineral resource concentration are areas underlain by coal, oil, gas, fluorspar, lead, zinc, limestone, dolomite, and sand and gravel. Coal mining perhaps presents the most serious conflict with waste disposal siting because of the need for coal and the likelihood of extraction where it is economically feasible. The locations of deep and strippable recoverable resources of the Springfield (No. 5) and Herrin (No. 6) coals in Illinois are shown in figures 15A through 15D.

Figure 15C Strippable reserves of the Herrin (No. 6) Coal (modified from Smith and Stall, 1975).

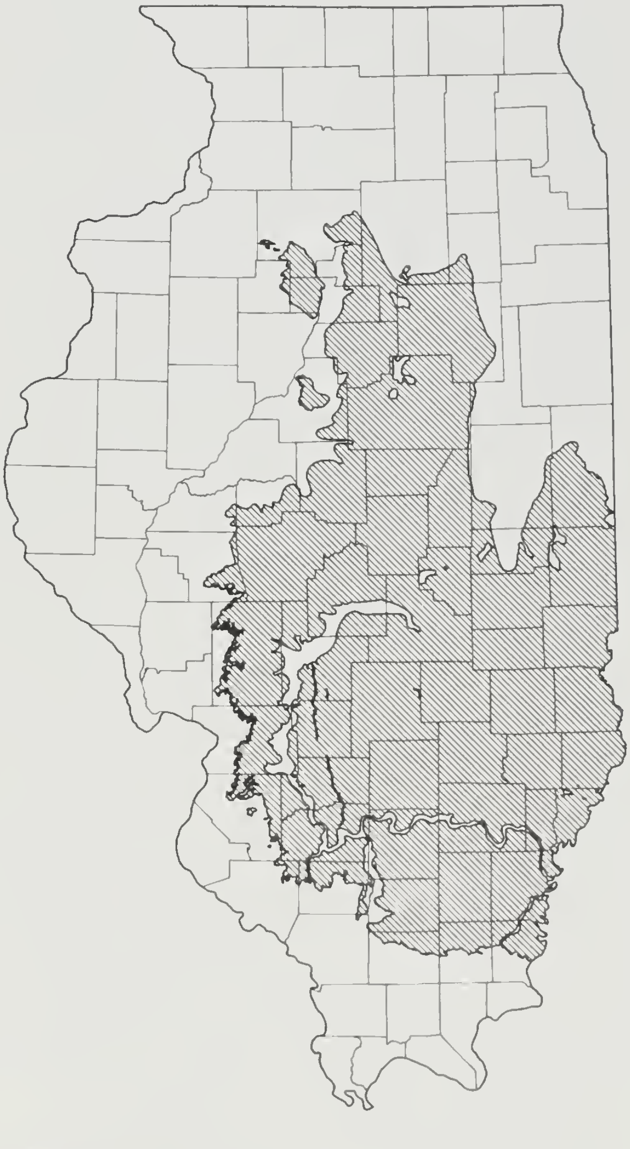


Figure 15D Deep resources of the Herrin (No. 6) Coal (modified from Smith and Stall, 1975).

MINED AREAS

Mined areas have had mineral resources extracted. For purposes of HW or LLRW disposal facility siting, this definition is expanded to encompass all disturbed lands, including those where fill has been removed and/or redeposited and those that have undergone extensive modification by construction activities.

Mining operations close to or within water-yielding materials may create avenues for rapid movement of groundwater and of HW or LLRW should a loss of containment integrity occur. Subsurface mining operations produce mine shafts and tunnels, which can create a groundwater system that is often complex and difficult to monitor. With shallow mining operations, fracture patterns may form above mine tunnels in overlying materials as a result of partial mine subsidence (Dunrud, 1976). Mines greater than 500 feet deep may have little effect on the hydrological characteristics of overburden materials. Unplugged or abandoned borings and wells (including those for coal exploration, oil and gas exploration and production, and water wells) could also provide pathways for the transmission of contaminants, if such a boring traverses a leaking containment structure.

Regions where extensive subsurface removal of minerals has occurred also may be unstable and prone to subsidence. Subsidence from deep mines commonly forms gentle depressions on the ground surface, which can alter surface-water flow and damage poorly designed containment structures. Pit-type subsidence from mines less than 200 feet deep could severely alter surface and near-surface conditions. Air photo interpretation and field information can be used to identify and evaluate subsided areas. In Illinois, information on the presence of underground mining is available from numerous coal maps constructed by the ISGS (figure 7) and from available maps of all coal and noncoal mines prepared by the ISGS for the Illinois Mine Subsidence Insurance Fund (Treworgy et al., 1989).

Surface-mined land (reclaimed or unreclaimed) and other disturbed areas often exhibit complex and variable distributions of materials, which are difficult to characterize hydrologically and geologically. In addition, disturbed materials may not stabilize for several years.

Regions that overlie mine shafts and tunnels probably should be excluded from consideration for disposal of HW or LLRW because of the potential for subsurface fracturing and subsidence. Some surface-mined land and disturbed land may meet many of the criteria discussed in this report for acceptable waste disposal. Other areas of disturbed land, such as small areas of fill extraction, should pose no problems for siting; nevertheless, detailed engineering and hydrological evaluations should be conducted to determine the stability of the disturbed material and to evaluate possible alterations in groundwater flow paths. Regions that have been subject to previous drilling operations (e.g., coal, oil, gas and water well drilling, or test borings) must be investigated very carefully to ensure that abandoned wells are properly plugged.

Siting facilitators should note that many of the studies and evaluations recommended in other sections of this report could require expansion or modification to permit an adequate evaluation of the special conditions encountered in mined areas.

SITE CHARACTERIZATION

INTRODUCTION

Site characterization, best defined by Siefken et al. (1982), is the process of investigations and tests, both in the field and laboratory, undertaken to define the site characteristics affecting the long-term stability of a disposal site and the interactions between the site and its surroundings. This section presents a detailed discussion of site characterization for HW or LLRW disposal with an emphasis on the application of steps and procedures that must be taken to achieve acceptable site characterization. Existing literature does not adequately address some of these steps, such as the design of a drilling program, groundwater characterization, and geomorphic characterization (landscape stability determinations). Discussions of specific site-characterization procedures reference other documents, principally McCray and Nowatzki (1985).

The topics discussed in this section are not presented necessarily in the order in which they are to be accomplished. The determination of site geology should be conducted before, in conjunction with, and following the drilling program. Site characterization involves the construction of site maps, use of analytical procedures, and the precise description of geologic materials (Landon and Kempton, 1971). We strongly recommend that geologic site characterization be conducted by a competent geologist familiar with the types of materials that are expected to be found at the site. Similarly, a competent hydrologist or hydrogeologist and geotechnical engineer or engineering geologist, also familiar with the region and types of materials at the site, should evaluate groundwater conditions and engineering characteristics of materials. Data collection and the description and evaluation of the geology, groundwater flow, and engineering properties of materials must be performed according to a rigorous format of quality control and assurance to ensure a high degree of confidence in the description of geological and hydrological conditions.

We suggest that geomorphic site characterization precede the drilling program and other site geological and hydrological investigations. Geomorphic site characterization may be performed concurrently with geomorphic area screening. Site characterization involves actual field measurement; area screening can be accomplished using existing information.

CONSTRUCTION OF A BASE MAP

An accurate, high quality base map is an essential prerequisite for successful characterization of a waste disposal site. McCray and Nowatzki (1985) present a detailed and comprehensive discussion of the importance of a base map and the techniques for its compilation for purposes of site characterization of a proposed LLRW disposal site. A summary of their recommendations follows.

Although the construction of a high quality base map may be relatively expensive, it is an integral part of the site-characterization process. The base map provides a place to record all important information accumulated prior to and during site characterization. The components of the map will vary with each site and be dependent on site characteristics and other factors, such as site size, topography, population and cultural features, pre-existing surveys, vegetation patterns, drainage patterns, the degree of accuracy desired, and economic constraints. The important factors that must be considered when establishing a base map are the scale and type of map and whether to use a pre-existing map or one constructed from a field survey.

The scale of each base map is extremely important. The proper scale should allow the entire project site to be represented on a map of reasonable size with all pertinent data displayed in an organized and uncluttered format. The use of transparent overlays for the presentation of various data is often a very useful technique in situations where large volumes of information are generated. Data accumulated during earlier selection stages that are relevant to the site-characterization study should be transferred onto the smaller-scale site-characterization base map. Construction of a base map should include the establishment of control points throughout the project site from which all other features within the site can be located.

Consideration must be given as to whether to use published maps or to create a map for the siting process. Initially, a thorough literature search should be undertaken to determine what maps are available. Once all the available mapping and aerial photography has been reviewed, a decision should be made as to whether a high quality base map for the project can be obtained from existing work. If a recent base map of high quality at an appropriate scale is available, then its use would be the most economical. If a suitable base map is unavailable for the project site, then one must be constructed. An extremely detailed topographic base map can be constructed from a high quality aerial photographic survey by using photogrammetric techniques. This type of survey is expensive and may not be warranted.

The common types of base maps are the topographic map and the planimetric map. Topographic maps are useful in areas where the ground surface elevation is variable. Planimetric maps, which do not depict elevation, are particularly useful in areas that are relatively flat and open. Distances, monument locations, dimensions, and boundary lines are normally presented on planimetric maps.

Aerial photographs may provide useful information to transfer to a base map. Photographs may be available for different dates, showing recent and seasonal changes important to the interpretations of the site. Aerial photographic coverage for nearly all of the United States and most of North America is available at one or more scales and for different years. A complete index of available aerial photographic coverage from the U.S. government is available through the U.S. Geological Survey EROS Data Center, Sioux Falls, South Dakota. Additional sources of aerial photography are state agencies and local aerial photographic contractors. A photographic survey of the site should be conducted, if one has not already been done by federal or state agencies or by private firms.

GEOLOGIC MAP CONSTRUCTION

To determine site stratigraphy and the relationship of site stratigraphy to regional stratigraphy, a detailed geologic map must be compiled from lithologic information. The geologic map is a basic component necessary to characterize the site and determine whether the site is suitable, from a geological perspective, for disposal of HW or LLRW. A stack-unit map format (which shows the areal distribution of geologic materials in their order of occurrence to a specific depth), such as presented by Berg, Kempton, and Stecyk (1984b) and Berg and Kempton (1988), is preferable.

A geologic map must include all information on the lithology of glacial and unconsolidated materials, soils, and bedrock deposits. Each stratigraphic unit and lithologic change within a stratigraphic unit should be accurately delineated and accompanied by an isopach map, which shows the thickness and areal extent of each unit.

The geologic map should be constructed in conjunction with the drilling program and other site-characterization procedures. Geologic maps are necessary so that comparisons between site geology and the previously determined regional geology can be made. Construction of geologic maps may reveal (1) the continuity of permeable materials or extensive zones of fracturing, and (2) potential problems that indicate the site is unsuitable and that the results of further exploration would be unsatisfactory and costly. Mapping also may show previously undetected zones of highly acceptable materials (e.g., a massive high clay-content aquitard) under all or part of the site. This preliminary finding may help make the drilling program more cost-efficient. Fewer bore holes may be required and exploration for secondary sites could be provisionally halted.

From information depicted on the geologic map, predictions can be made regarding the repetitive sequences of materials expected at a site. Whether a site contains complex lateral and vertical discontinuities will first become apparent on preliminary geologic maps. Prevalence of these features on final maps may result in exclusion of the site from consideration for HW or LLRW disposal.

LANDSCAPE STABILITY

Two significant elements of landscape stability related to and dependent upon site geology should be considered in siting HW and LLRW disposal facilities: the sensitivity of a landscape to mass movements and the susceptibility of a site to erosion by geomorphic processes (eolian activity [wind], fluvial processes, and overland flow). Landscape instability and associated landform erosion may (1) undermine a disposal facility, resulting in damage to the containment system, its protective dikes, and other surficial containment structures; (2) alter the extent of flood hazard areas; (3) erode and undercut hill slopes, resulting in mass movements; and (4) require excessive continued maintenance (repair) of the disposal facility. Excessive erosion also can increase the distribution of released contaminants to the surrounding region and reduce the length of pathways from near-surface disposal deposits to the ground surface.

Geomorphic landscape stability is one of the most complex and controversial concepts of surficial geology, and an in-depth discussion of the topic is beyond the scope of this document. Readers are urged to consult Birkeland (1974); Dunne and Leopold (1978); Gardiner and Dachombe (1983); Leopold, Wolman, and Miller (1964); Ritter (1978, 1986); Way (1978); Schumm (1977); Thornes (1979); and Wells et al. (1985). This section of the report emphasizes steps that should be taken to evaluate the overall stability of a landform. Susceptibility of landforms to mass movements and techniques for investigating susceptibility are discussed in detail under the next heading. Several geomorphic concepts, steps, and procedural recommendations for investigation should be utilized to determine the stability of landscapes for HW or LLRW disposal. A conservative approach has been adopted for assessing landscape stability because it cannot be assumed that present-day environmental conditions (i.e., climate and land-use) will persist throughout the waste containment period.

It is imperative that the types and rates of geomorphic processes operating in the vicinity of a proposed HW or LLRW disposal site be examined with respect to their potential to influence the integrity of the site. Four steps that should be followed to determine the stability of a landform are:

- *Evaluation of the long-term stability of a proposed disposal site.* Provided that modern geomorphic processes are not significantly modifying the landscape, "old" stable landforms should be selected for disposal in preference to younger landforms because (1) they have a long-term history of stability, and (2) past geomorphic events can influence modern earth surface processes and provide a predictive measure for the future long-term stability of a site (Wells et al., 1985). Long-term landform stability can be assessed by comparing landscapes of similar age and glacial histories.

- *Evaluation of short-term (modern) geomorphic processes that might influence "old" (stable) landscapes.* The effect of geomorphic hazards—processes operative during a period of instability (see below)—on a landscape proposed for HW or LLRW disposal should be defined by measurable variables that characterize the form and flux of energy and mass (by erosion and deposition) within the system. Studies to determine the geomorphic "adequacy" (the ability of the site to meet the desired performance objectives) should (1) identify and measure geomorphic variables that characterize landforms and landform elements within the watershed of disposal, (2) evaluate the short-term rate of change in these geomorphic variables induced by geomorphic processes, and (3) identify geomorphic processes (hazards), using 1 and 2 above, that can affect "old" stable landscapes. Geomorphic hazards of importance are:
  - river bank erosion and meander growth
  - channel headcutting and gullying
  - drainage network rejuvenation and extension
  - channel aggradation and incision
  - vertical downwasting of slopes
  - valley floor aggradation and degradation

The relative importance of any geomorphic hazard depends on its magnitude; that is, processes occurring at the highest rates represent the greatest hazard to a disposal site (Wells et al., 1985). Landforms or portions of landforms that will be affected by these geomorphic hazards should not be considered for HW or LLRW disposal.

- *Evaluation of the potential of an "old" stable landform or landform component to become unstable.* This involves determining the threshold conditions whereby changes in geomorphic processes occur and significantly modify the landscape. Stable landforms may be approaching a threshold condition which, once exceeded, will result in landscape instability or modification. A valley floor, for instance, may become unstable and gullying may be imminent once a geomorphic threshold is exceeded. Siting studies should attempt to identify the existence of geomorphic thresholds, for example, through detailed analyses of the relationship of slope and gradient to material type. These data should be used to avoid the disposal of HW or LLRW upon or within landforms that are prone to geomorphic hazards.

- *Evaluation of changes in landscape form and rates of operative geomorphic processes in response to man-induced disturbances.* Studies of candidate sites should evaluate the effects of present or future disturbances to a geomorphic system, including stream channelization or flow detention, mining activities, and land-use changes. It is important that studies to determine the effect of disturbances should compare differences in geomorphic variables and rates of geomorphic processes between undisturbed and disturbed systems of similar climate, bedrock, and geomorphic history (Wells, 1982).

We also recommend that disposal facilities be located as far from upstream drainage basin areas as possible to minimize the potential for headward erosion into the uplands by streams and gullies. Because the types and rates of geomorphic processes vary by both time and location, it is impractical, if not impossible, to describe exact procedures and techniques to use in geomorphically analyzing the stability of a proposed disposal site. Hence, we suggest that studies of geomorphic landscape stability be conducted by trained geomorphologists using data pertaining to geomorphic variables (e.g., channel dimensions and valley floor dimensions) in conjunction with stratigraphic, sedimentologic, and geomorphic principles.

MASS MOVEMENT SUSCEPTIBILITY

Mass movement susceptibility is the tendency of geologic materials to move. It involves the downward relocation of materials in the form of slumps, flows, and landslides. It is a subcategory of landform stability; however, separate techniques of investigation are necessary to evaluate its ramifications. Three major categories of susceptibility to mass movements have been identified by Carson and Kirkby (1972): (1) slides, downward slope failures initiated by movements along well-defined planar surfaces, (2) flows, the downward movement of slope material by differential shearing within the transported mass, and (3) heave, the upward movement of slope material perpendicular to the ground surface caused by expansion of constituents, which facilitates rapid downslope mass movements.

Rapid mass movements of unstable slopes may damage or rupture a poorly sited HW or LLRW containment system or result in the downslope dislocation of a facility or portion of a facility, exposing waste for distribution to adjacent areas. Flows and slides of surficial material also could alter directions of groundwater and surface-water flow, rendering monitoring programs ineffective. Changes in surface-water hydrology could result in increased gullying and surficial erosion, which in turn could impact the overall stability of the site.

A two-phase approach should be used to investigate landscape stability with respect to mass movements. Phase I involves determining the susceptibility of the site to mass movements. Phase II involves studying the stability of slopes adjacent to a proposed site by using a limit equilibrium analysis (e.g., Morgenstern and Sangrey, 1978), which deduces slope performance in terms of safety factors.

The initial stages of a Phase I investigation should involve the examination of the landscape topography. Determination of relief and slope should be accom-

Table 4. Basic factors considered in evaluating a geologic terrain (from Rib and Liang, 1978).

Factor	Element	Examples
Geologic	Landform	Geomorphic history; stage of development
	Composition	Lithology; stratigraphy; weathering
	Structure	Spacing and attitude of faults, joints, foliation, and bedding surface
Environmental	Climate and hydrology	Rainfall; stream, current, and wave actions; groundwater flow; slope exposure; wetting and drying, frost action
	Catastrophes	Earthquakes; volcanic eruptions; hurricanes, typhoons and tsunamis; flooding; subsidence
Human	Human activity	Construction; quarrying and mining; stripping of surface cover; overloading, vibrations
Temporal[a]		

[a]Common to all categories and factors.

plished initially. Often, regions of high relief can be classified as having excessive erosion, a high hydraulic groundwater gradient, a high potential for slope failure, and an increased difficulty for site construction. Hence, several states recommend maximum limits of relief and slope. In Pennsylvania, for example, recommendations state that the relief within 1 kilometer of a proposed site should not exceed 150 meters (Witzig, Dornsife, and Clemente, undated); in Missouri, South Carolina, and Colorado, it is recommended that slopes not exceed 5 percent within or adjacent to a proposed site (Monnig, 1984). These restrictions are, however, arbitrary and some geological conditions may render slopes of less than 5 percent unstable during particular seasons or climatic events. Consequently, we recommend that relief and slope should be minimized at a HW or LLRW disposal site; however, there must be sufficient slope (greater than 0 percent) to allow site drainage.

In addition, more detailed terrain analysis should be conducted to determine the mass movement susceptibility of a proposed disposal site. Rib and Liang (1978) suggest that certain terrains are more susceptible to mass movements than others because of variances in and interactions between the geology, climate, hydrology, and man-induced alterations (table 4). For example, landforms composed of alternating layers of pervious and impervious geologic materials, or landforms that possess numerous planes of structural weakness, are highly susceptible to mass movement. Certain portions of landforms are also more vulnerable to rapid mass movements than others, such as: (1) cliffs, banks, or steep slopes undercut by stream or wave action, (2) areas of concentrated drainage or seepage, and (3) areas of hummocky (irregular and rugged) ground (Rib and Liang, 1978). Such regions of unstable terrain should be identified and excluded from waste disposal.

Phase II, the limit equilibrium analysis of landscape susceptibility to mass movements, should be conducted on all slope surfaces of significant extent within or immediately adjacent to a proposed site. The limit equilibrium analysis evaluates the performance of a slope in terms of a factor of safety F (Morgenstern and Sangrey, 1978). This analysis examines the stability of rock or soil slopes under the assumption that incipient failure occurs along a slip surface.

The adequacy of limit equilibrium procedure(s) chosen for use at proposed HW or LLRW disposal facilities will likely vary widely depending on site geology (e.g., structural discontinuities, earth material sedimentology/stratigraphy, or geologic unit homogeneity/isotropy). Of most importance to waste disposal problems in Illinois, for example, are methods applicable to curved or arbitrarily shaped failure surfaces, which are common to slopes of cohesive sediments. Numerous limit equilibrium methods have been devised for soil (regolith) slopes. Several of these procedures and their associated references are listed in table 5 and are summarized in Anderson and Richards (1978), Attewell and Farmer (1974), Chowdhury (1978), and Terzaghi and Peck (1967). A discussion pertaining to the choice of limit equilibrium techniques to particular problems is found in Chowdhury (1978).

REMOTE SENSING AND GEOPHYSICAL EXPLORATION

Remote sensing and geophysical exploration techniques should be used to delineate land-use and earth material types and to detect the presence of near-surface and deeper permeable materials. We strongly advocate a well-integrated program of geological and geophysical investigations. Many geophysical techniques rely on boreholes and therefore can be done

Table 5. Summary of several selected slope stability methods suitable for curved or composite failure surfaces and for heteregeneous, unconsolidated earth materials (modified from Chowdhury, 1978).

Method	Use	Reliability	Reference
Fellenius	Applicable only to circular failure surfaces. Determination very simple; no iteration required.	Underestimates factor of safety	Fellenius (1936); Taylor (1937, 1948)
Bishop simplified	Restricted to circular slip surfaces. Iterative procedure required for solution, but useful for hand calcutions. Errors possible where portion of slip surface has steep negative slope near toe.	Fairly accurate	Bishop (1955); Whitman & Bailey (1967); Bishop & Morgenstern (1960)
Janbu	Suitable for slip facies of arbitrary shape. Iterative procedure required for solution; computer desirable.	Fairly accurate	Janbu (1954, 1957); Wright (1975); Hirschfeld & Paulas (1973)
Morgenstern and Price	Versatile method that satisfied both force and moment equilibrium. Suitable for slip surface of arbitrary shape and boundary conditions. Computer necessary. Considerable experience and judgment required to use procedure reliably.	Fairly accurate	Morgenstern & Price (1961); Morgenstern (1968); (1968); Hanel (1968)
Spencer	Applicable to circular or non-circular slip surfaces. Use of computer desirable.	Acceptable	Spencer (1973); Wright (1975)

only following or in conjunction with the drilling program. Other geophysical techniques (as well as remote sensing) may be used to design the drilling program more efficiently; therefore, they must precede or be coordinated with the drilling program.

Geophysical exploration should be used to detect material differences at depth; the techniques should be sensitive enough to delineate the presence of permeable materials or materials of different densities. The technique cannot replace a detailed drilling program. Geophysical methods also should be used to extend detail of an investigation beyond the limits of a drilling program and to assist in stratigraphic correlations, for example, to an area where the presence of highly permeable materials in the subsurface is suspected. Geophysics is particularly important for determining the depth to bedrock, and down-hole geophysics is extremely helpful in defining materials between sampled intervals. For a detailed discussion of geophysical applications for disposal facility siting see McCray and Nowatzki (1985).

DRILLING PROGRAM

The drilling program at a HW or LLRW disposal site should be multiphased, starting with the drilling of one or more initial characterization borings followed by at least two phases of additional borings and material characterization. The purpose of the drilling program is to characterize the stratigraphy and, in so doing, provide a basis for predicting the sequence of geologic materials at a site. In particular, the drilling program should be designed to determine the presence of highly permeable materials within 90 meters of the surface and the presence of intensively weathered and extensively fractured materials. Drilling also provides the opportunity to collect geologic samples for inspection and testing. In addition, monitoring wells and piezometers can be constructed in boreholes, as can *in situ* pressure tests.

The degree to which site geology and hydrology can be predicted depends on a well-designed drilling program. Each phase of the drilling program should include:

- material sample collection and description, including field tests for hydraulic properties of materials;
- laboratory analyses for physical properties, including grain size, hydraulic characteristics, geochemical properties (such as adsorption characteristics), engineering properties (such as Atterberg Limits), and other pertinent data for each geologic unit encountered;
- detailed description of the site stratigraphy and mapping of stratigraphic units; and
- delineation of the groundwater system, including the top of the zone of saturation, potentiometric surfaces of any aquifers present, and the rates and directions of groundwater movement (both vertically and horizontally).

The approaches to determining the above parameters are discussed in other sections of this report.

Regional geologic mapping provides information on which to base initial predictions of the sequence of geologic materials expected at a candidate site. The amount of geological and hydrological information required to characterize a site depends on whether the geologist is able to make reliable predictions regarding geological conditions (and groundwater movement). Prediction here refers to the ability to predict the depth, thickness, and lithology of each geologic unit at any given point within the site. A site is considered adequately characterized when such prediction is possible. If site variability limits the ability to make reliable predictions regarding geological conditions or groundwater movement, then the site is not suitable for HW or LLRW disposal.

Phase I and II drilling. The initial site-characterization boring or borings (Phase I of the drilling program) should be positioned near the center of the site (drilled to at least 90 meters) unless there is a better reason to drill elsewhere (e.g., the suspected presence of a major geological element, such as a bedrock valley). However, if at all possible, drill holes made during all phases of site characterization should not be placed within the actual area where the waste is to be stored (if known). This would also apply to the digging of test pits. If drilling is done in this area, drill holes should be properly sealed to prevent downward leakage of contaminants.

The geological information from the initial boring or borings should verify whether conditions at the site are consistent with the regional and area geological data. A decision then should be made whether to drop the site from consideration or to undertake a more detailed drilling program. The presence of highly permeable materials within 90 meters of the surface, for example, may warrant elimination of the site from further consideration.

If further drilling is undertaken, we suggest that Phase II of the drilling program consist of a generic test boring and exploration program, the extent of which is controlled by the geometry, topographic variability, and geological complexity of the site. If geological conditions are found to be relatively uniform, the site is more predictable and fewer borings will be required.

The test drilling program should be designed to test a conceptual model of the geology and hydrology. Borings should be located to provide the maximum amount of geological and hydrological data. If there is no geological reason for choosing one drilling location over another, a generic test drilling program initially may involve borings placed at the corners of a site as well as spaced equidistant between corners. One or more borings should have already been completed in the middle of the site. It is essential that one or two of the borings be drilled at an angle to determine the relative extent of fracturing in the materials.

All borings in this second phase should extend to at least 90 meters. If bedrock is encountered and the sequence of bedrock materials is consistent between borings, then subsequent borings should concentrate on adequately characterizing overburden (Quaternary) materials.

If surface topography is irregular, borings also should be completed on the topographic highs and lows within the site. These borings would identify the possible existence of different materials situated in their respective topographic positions. Monitoring of the shallow groundwater system could be affected by differences in elevation at the site. We recommend that piezometers or observation wells be established on topographic highs and lows. If test borings from Phase II drilling indicate that variable or unfavorable conditions exist, such as the presence of highly permeable materials within 90 meters of the surface, intensively weathered materials, or extensive fracturing or joints as shown by angle borings, then the site probably should be dropped from further consideration.

Phase III drilling. A third, more detailed exploration program should follow if the geological information derived from Phase II indicates that the site appears favorable, such that (1) permeable materials of high hydraulic conductivity (or aquifers) are not present within 90 meters of the surface, or it has been determined that groundwater travel time from the surface to a highly permeable material is within acceptable limits (e.g., 500 years for LLRW), (2) a relatively uniform and predictable sequence of geologic materials has been found, (3) intensively weathered materials are generally absent, and (4) extensive fracturing of materials has not occurred.

Phase III of the drilling program is inherently related to information derived from Phases I and II. If there is no occurrence of or no apparent recognizable pattern to the subsurface occurrence of permeable, weathered, or fractured materials, then borings again should be spaced equidistant between previous borings. If highly permeable materials, weathered materials, or fracturing are still not discovered, suggesting that geologic materials at the site are relatively uniform and predictable, then geological information characterizing the site is considered adequate.

If highly permeable materials or weathered materials or extensive fracturing encountered in this phase of drilling appear to be continuous, then additional borings should be completed. The location of on-site borings should be dictated by the geology. If it is suspected that unfavorable conditions are present in one particular portion of the site, then borings should be concentrated in that portion of the site in order to delimit the areal extent of these conditions.

Off-site investigations. If highly permeable materials or intensively weathered materials discovered in any portion of the site appear to extend beyond site boundaries, then off-site exploratory borings are required to assess the continuity of these weathered or permeable materials. The depth of off-site borings need not be significantly deeper than the geological feature being traced from the on-site location. The number and location of off-site borings would depend on the local complexity or variability indicated by geological information from on-site borings. However, extensive off-site drilling often is hindered by the problem of obtaining access to suitable drilling locations; thus it can be difficult to accurately trace and map geologic materials off the site.

If off-site investigations indicate that these materials are not continuous, then the site may be considered preliminarily favorable and further investigations and additional on-site drilling may proceed. However, if off-site exploratory drilling suggests that on-site aquifers, potential aquifers, or other highly permeable materials or intensively weathered materials are continuous to off-site locations, then the site should not be considered further for disposal of HW or LLRW.

Adequacy of the drilling program. The geological information about the site is considered adequate if, after the drilling program, it is determined that the sequence of geologic materials present is predictable. A site is considered preliminarily suitable for HW or LLRW disposal only when it can be shown as a result of a drilling program that (1) aquifers or other highly permeable materials are not present within 90 meters of the surface, or it has been determined that groundwater travel time to an aquifer is acceptable, (2) strongly weathered materials are absent, and (3) highly permeable materials or weathered materials and extensive fracturing are not continuous within the site and are not continuous from within the site to off the site.

The drilling program is only one of several steps in determining the overall geological and hydrological suitability of a proposed HW or LLRW disposal site. Although preliminary geological information from a drilling program may suggest that the site is suitable for disposal, the final determination of site suitability can be accomplished only following detailed field and laboratory analyses of materials, evaluation of site hydrology through modeling (from which transport time can be estimated), and verification of the absence of any exclusionary criteria.

SITE STRATIGRAPHY

A review of reported cases in which HW or LLRW disposal facilities have failed to adequately contain contaminants indicates that most, if not all, containment failures are the result of either poor identification and characterization of geologic materials or failure to consider geological criteria during the siting process. For example, problems at the Sheffield LLRW and Wilsonville HW disposal sites in Illinois are primarily the result of complex geological settings that should have been more completely characterized prior to facility operation.

A thorough understanding of the geological setting (sedimentology and stratigraphy) of a candidate site is essential to proper siting and site characterization of a HW or LLRW disposal facility. The sedimentology and stratigraphy may reveal certain geochemical and hydrogeological properties of the materials. Some materials transmit contaminants easily, and others restrict the movement of or adsorb contaminants, thereby lessening the potential for rapid movement of contaminants in groundwater.

Material sample collection and analysis. Sample collection should provide adequate material for sufficient laboratory analyses to augment field descriptions and also to provide reliable data on earth-material characteristics. The following procedures should be followed:

- *Detailed field notes should be taken during sample collection.* Notebooks must be signed and dated and other quality control and assurance procedures described and followed. All bedrock types, glacial deposits, and soils should be identified. Lithology, thickness, color, structure, carbonate content, weathering characteristics, fabric, and nature of contacts between deposits must be carefully described.
- *Stratigraphic terminology should be described consistent with current stratigraphic nomenclature.* In Illinois, this would include Berg et al. (1985); Lineback et al. (1979); Treworgy, McKay, and Wickham (1979); and Willman et al. (1975).
- *Samples should be taken continuously while drilling.* If complexity in the sequence of materials is indicated, samples should be analyzed within each of the different identified units. If materials are relatively uniform, samples should be obtained at 1.5-meter intervals. Cores collected through a hollow-stem auger by Shelby tube or similar samplers provide the best geologic samples in glacial materials, especially where fine-grained materials predominate. Diamond bit coring should be used for bedrock drilling. Samples collected by these methods will be relatively undisturbed and will provide a complete record of the materials penetrated.
- *Samples should be collected from angled drill holes, and test pits should be excavated to thoroughly explore the upper 10 meters of materials.* Test pits are especially helpful for determining the continuity of recognized stratigraphic units and, together with cores collected from angled drill holes, for exploring for fractures and highly permeable materials. Sampling of materials from walls of test pits should be done along vertical profiles. If materials in the pits are relatively uniform, then fewer profiles are needed. If complexity or variability in the sequence of materials is indicated, samples should be analyzed from all recognized geologic units.
- *Particle size should be determined using the standard pipette procedure discussed by Klute (1986).* Grain-size distribution can provide a crude indication of hydraulic conductivity of geologic units (Berg, Kempton, and Stecyk, 1984b). Sands and gravels typically have higher hydraulic conductivities than silts and clays. A summary of various grain-size classifications is shown in table 6. Hydraulic conductivities typical of various geologic materials are shown in table 7. Small changes in grain size can affect the downward movement of water through soils due to gravity and capillary forces (Berg, 1984). Capillary discontinuities and capillary forces in general are related to pore size, which is also a function of grain size. Capillary discontinuities in materials underlying a waste containment

Table 6. Summary of various grain-size classifications commonly in use (Blatt, Middleton, and Murry, 1980).

Udden-Wentworth	ϕ values	German scale[1] (after Atterberg)	USDA and Soil Science Society of America	U.S. Corps Engineers Dept. Army and Bureau Reclamation[2]
		(Blockwerk)		
Cobbles		200 mm	Cobbles	Boulders
			80 mm	10 inches
64 mm	-6			Cobbles
				3 inches
		Gravel		
Pebbles		(Kies)		Gravel
4 mm	-2		Gravel	
				4 mesh
Granules				Coarse sand
2 mm	-1	2 mm	2 mm	10 mesh
Very coarse sand			Very coarse sand	
1 mm	0		1 mm	
Coarse sand		Sand	Coarse sand	Medium sand
0.5 mm	1		0.5 mm	40 mesh
Medium sand			Medium sand	
0.25	2		0.25	
Fine sand			Fine sand	Fine sand
0.125	3		0.10 mm	
Very fine sand			Very fine sand	200 mesh
0.0625 mm	4	0.0625		
			0.05 mm	
Silt		Silt		
			Silt	Fines
0.0039 mm	8			
		0.0002	0.002 mm	
Clay		Clay	Clay	
		(Ton)		

[1] Subdivision of sand sizes omitted.

[2] Most numbers are for U.S. Standard sieves: 4 mesh = 4.76 mm; 10 mesh = 2.00 mm; 40 mesh = 0.42 mm, 200 mesh = 0.074 mm.

system can be recognized only during detailed sampling of excavations and test borings and by analyses of samples for grain size and other material properties.

- *The clay-mineral composition of the less-than-2-micron portion of materials should be analyzed according to the procedure of Glass as reported in Hallberg, Lucas, and Goodmen (1978) and Killey (1982).* Adherence to this particular procedure will permit easy comparisons with clay-mineral determinations conducted on samples in the Midwest. The clay-mineral composition of geologic materials is important because it indicates the potential of the clay to swell and shrink as a result of wetting and drying, and it provides an estimate of the potential for leachate adsorption. For example, smectites, expandable clay minerals subject to extensive shrinking and swelling, constitute 60 to 70 percent of the clay fraction of surficial windblown loess [15-20 percent clay-size] in Illinois, whereas the clay fraction of most diamictons [30-35 percent clay-size] is composed of 55 to 80 percent illite, a nonexpandable or low-expandable clay mineral. Cation-exchange capacity (CEC), which is a major factor in the attenuation of some HW constituents and radionuclides, is dependent on the species of clay minerals present in materials. Higher CEC values generally are associated with expandable clay minerals rather than with illite, kaolinite, and chlorite because of the large number of exchange sites on expandable clay particles. Clay mineralogical investigations also are essential to site characterization because they can aid in:
  - predicting weathering rates of various materials
  - determining engineering characteristics of deposits
  - determining the total ion exchange capacities and adsorption potentials of geologic materials
  - identifying soluble minerals and background sources of contaminants (either natural or man-made)

Table 7. Summary of hydraulic conductivities typical of various geologic materials (Berg, Kempton, and Cartwright, 1984a).

Geologic material	cm/sec	gpd/ft^2	Comments
Clean sand and gravel	1×10^{-3}	> 20	May be highly permeable
Find sand and silty sand	1×10^{-5} to 1×10^{-3}	0.2 to 20	—
Silt (loess, colluvium, etc.)	1×10^{-4} to 1×10^{-4}	1×10^{-1}	—
Gravelly till, less than 10% clay	1×10^{-7} to 1×10^{-5}	2×10^{-3} to 2×10^{-1}	Often contains gravel/ sand lenses or zones
Till, less than 25% clay	1×10^{-8} to 1×10^{-6}	2×10^{-4} to 2×10^{-2}	Often contains gravel/ sand lenses or zones
Clayey tills, greater than 25% clay	1×10^{-9} to 1×10^{-7}	2×10^{-5} to 2×10^{-3}	Often contains gravel/ sand lenses or zones
Sandstone	$> 1\times10^{-4}$	> 2	—
Cemented fine sandstone	1×10^{-7} to 1×10^{-4}	2×10^{-3} to 2	Frequently fractured
Fractured rock	$> 1\times10^{-4}$	> 2	May have extremely high hydraulic conductivity
Shale	1×10^{-11} to 1×10^{-7}	2×10^{-7} to 2×10^{-3}	Often fractured
Dense limestone/dolomite (unfractured)	1×10^{-11} to 1×10^{-8}	2×10^{-7} to 1×10^{-4}	—

- evaluating the organic component of the earth materials (McCray and Nowatzki, 1985)

- *Determination of carbonate content, diamicton fabric, heavy mineral composition, moisture content, porosity, hydraulic conductivity, bulk density, ion-exchange capacity, pH, mineralogy, and reaction should all be done during site characterization.* A standard reference for procedures is available in Page (1982) and Klute (1986). Carbonate analysis determines relative percentages of calcite and dolomite in a geologic material. Carbonate values may vary between depositional units and can provide an index of soil weathering. Heavy mineral analyses identify mineral suites that often are characteristic of a particular deposit (Willman, Glass, and Frye, 1963). Diamicton fabric analysis may give an indication of the direction of movement of ice that deposited different unconsolidated glacial materials and/or their modes of deposition, both of which are useful for determining stratigraphic relationships. The procedure outlined by Lawson (1979) is commonly used.

- *Following identification and characterization, the geologic sequence should be recorded and materials correlated locally (the test site) and regionally (Landon and Kempton, 1971).* Both the horizontal and vertical distribution of earth materials should be identified, described, and mapped in detail. If geologic materials cannot be characterized and correlated with only the aid of grain-size and clay-mineral analyses, then tests for carbonate mineralogy, heavy minerals, and diamicton fabric should be performed. For routine regional stratigraphic investigations, the use of grain-size distributions and clay-mineral compositions are usually adequate to augment field and other lithologic studies for identifying materials. Grain-size distributions and clay-mineral compositions have been used extensively and with great success in correlating glacial stratigraphic units. (Kempton, Berg, and Follmer, 1985; Willman and Frye, 1970). From this, the character and areal extent of aquifers and aquitards can be postulated, as well as their position in a particular stratigraphic sequence. In addition, the location of highly permeable materials can be noted.

STRUCTURAL FEATURES

A comprehensive site characterization analysis for a HW or LLRW disposal site should involve a detailed assessment of structural features. These include features that formed during deposition of a sediment and after deposition. The former includes such features as the nature of the bedding and stratification. Postdepositional features include fractures (faults and joints) and folds.

Site characterization should focus particular attention on bedding planes, fractures, and joint patterns. Fracture zones between blocks of rock that have not been displaced relative to one another are called joints. Bedding planes are the surfaces between beds (seams of geologic material younger than the material below and older than material above). Bedding planes provide natural horizontal flow paths for groundwater.

Fractures and bedding planes. Regions of geologic materials exhibiting numerous fractures and bedding planes provide (1) avenues for potential migration of hazardous waste or radionuclides from a disposal facility, (2) increased infiltration of surface water and contaminants, and (3) interaquifer exchange of contaminants. Fracture zones at or near the surface or at depth may channel water to the surface over a particular portion of the site, thereby increasing channelized flow and surficial erosion. In addition, fracture density and orientation can affect the stability of trench walls surrounding containment structures by lowering the shear strength of a material. Finally, some bedding planes and fracture systems, particularly between materials of distinct lithologic character, may act as planes of weakness resulting in slope failure and mass movements.

Major textural discontinuities also could result in preferential flow paths for contaminants along the contact between the geologic units. Because groundwater flow is often rapid and localized in fracture zones, the migration and dispersion of hazardous waste or radionuclide leachate is difficult to predict.

A literature search of geological documents pertinent to the vicinity of the candidate site may prove to be particularly useful because the regional geologic structure is often similar to that expected at the site. Extensive fracturing and joints, as well as bedding structures and stratigraphic breaks, should be described on a regional basis with respect to a particular geologic unit. When that particular geologic unit has been identified at a candidate site, it most likely will exhibit characteristics described regionally. The most accurate method for describing structural features is field mapping.

Perhaps the most significant and common structural feature that could have the potential to cause exclusion of a site from HW or LLRW disposal is the presence of extensive fracturing, either in bedrock or glacial materials. This and other types of structural discontinuities can severely increase permeabilities. We recommend that angle borings be drilled at a minimum of two locations on the candidate site to determine the presence of these vertical discontinuities. We further recommend that sites with extensive fracturing be excluded from consideration for HW or LLRW disposal.

Faulting and folding. If extensive areas of inactive, minor faults are discovered at the bedrock surface, a monitoring program must be designed to discover whether the faults adversely affect groundwater movement. Minor displacements of bedrock materials by small, long-inactive faults are commonplace and may be expected at candidate sites. In many situations, minor displacements at depth could actually improve site performance by creating barriers to potential contaminant migration. The presence of minor inactive faults at depth should not be considered a hindrance to effectively monitoring a site. But this characteristic should not be actively sought in the siting process. If these features are encountered by chance, their effect on site integrity must still be evaluated.

Geophysical exploration techniques can be employed to evaluate the extent of some structural features. Seismic reflection and gravity and magnetic surveys may be helpful in locating faults and other features, depending on the geological setting.

MATERIAL WEATHERING

Weathering is the physical, chemical, and biological alteration (decay) of rocks and minerals. Weathering includes soil-formation processes and the alteration of parent material along joints or fractures. A soil is described by Birkeland (1974) as a "natural body consisting of layers or horizons of mineral and/or organic constituents of variable thickness, which differ from the parent material in their morphological, physical, chemical, and mineralogical properties and their biological characteristics."

Pedologic characterization requires the description of soil fabric, structure, color, and horizonation. Soil fabric is the arrangement of individual soil particles. Soil structure (blocky, angular, massive) is the formation and arrangement of individual aggregates of soil particles referred to as peds. Soil horizonation refers to the formation of zones within a soil profile reflective of processes of additions, removals, transformations, and translocations of soil material and associated chemical properties. Differences in soil color usually are associated with different soil horizons. Other features that may be described are the presence of secondary minerals, as well as concretions, jointing, and fracturing.

Weathering causes physical and chemical changes in the parent rocks and minerals that make up a geologic unit. This may affect several properties of the unit, including: (1) engineering characteristics (e.g., shear strength, compressibility, and density), (2) cation-exchange capacity, (3) organic matter content, (4) the chemical composition of the material and pore water, and (5) hydraulic properties (McCray and Nowatzki, 1985). In addition, pedologic evaluation of materials at a site is important to avoid overlooking elements that could drastically affect the performance of a HW or LLRW disposal site. Follmer (1984b), in evaluating pedologic parameters at the Wilsonville hazardous waste site in Macoupin County, Illinois, reported that poor site performance was in part the result of failure to recognize certain pedologic features within and adjacent to disposal trenches: contaminant migration could have been better predicted if physical soil features such as horizonation, fabric, and structure had been described.

Buried soils in the Midwest, often within 6 meters of the surface, as well as deep weathering in modern soils may provide pathways for the transmission of contaminants along material boundaries or in joints and fractures within the zone of weathering. In Illinois, for example, the most pronounced buried weathering horizon is associated with the Sangamon Soil (Follmer, 1984a). Identifying characteristics of the Sangamon Soil are similar to those for surface weathering zones; however, the depth of weathering from the Sangamon Soil is often considerably deeper than for the modern soil. A description of pedologic investigations necessary for identification of material weathering at waste disposal sites is presented by Follmer (1984b).

Intensively weathered materials near the surface can be identified during field work, particularly in natural exposures and test pits. Identification of weathered materials also can be done during sample collection and description in the drilling program. Weathering will almost always be associated with materials at the surface. The extent of weathering can be determined by the depths of leaching, oxidation, root penetration, and hairline fractures and joints. Clay and silt coatings often will permeate fractures and joints. Soils should be described according to U.S. Department of Agriculture specifications.

Identification of weathered horizons in the deep subsurface, either in glacial materials or bedrock, can be accomplished only during the drilling program. Exclusion of a site on the basis of weathering of near-surface or deeper subsurface strata may be necessary if the weathering inhibits adequate characterization and modeling, or if it results in increased groundwater velocities. Regions where weathering may significantly decrease site performance or monitorability should be avoided for HW or LLRW disposal.

ENGINEERING PROPERTIES

Engineering properties refer to geotechnical characteristics inherent within a geologic material. These can affect the design, construction, and performance of a HW or LLRW containment system. A thorough engineering investigation involves the study of material properties that could affect the capability of a site to withstand natural and man-caused events.

Engineering tests are designed to test for particular construction needs. Engineering test procedures must be evaluated independently to ensure their applicability to the geologic material in question. Considerable care must be used before choosing one method over another. Investigations are best dealt with by an engineering geologist or earth materials engineer familiar with the geologic materials in the region of a candidate site. A complete discussion of geotechnical investigations is beyond the scope of this report. A good review of the methodologies of numerous engineering tests necessary for proper site characterization is presented by McCray and Nowatzki (1985). Numerous engineering parameters and their methods for evaluation are listed in table 8. Several geotechnical considerations are described briefly in the following paragraphs.

Shear strength. Shear strength is the capacity of materials to resist shear stresses on a given plane of orientation. The shear strength of a geologic material is influenced by many factors, including physical and chemical properties of the material, hydraulic properties of the groundwater regime, and the stress history of the material at a given site. Shear strength tests are used to determine the bearing capacity and slope stability of a material at a given site, which in turn can affect structure stability. Shear strength is one factor used in determining what type of foundation is to be constructed.

Settlement. Settlement is the subsidence of material caused by a reduction of pore space or the flow of material in response to loading. Settlement may cause differential movement and consequently damage a HW or LLRW containment system. In sandy soils, settlement may occur rapidly; in clayey materials it is generally slower. Settlement in clay soil is caused by the expulsion of air and pore water from void spaces, as well as particle flow (creep) under static load. The rate and amount of settlement is a function of material type, moisture content, and size and distribution of load.

Table 8. Summary of selected engineering parameters and associated evaluation technique references (modified from McCray and Nowatzki, 1985).

	Technique	Reference
Parameter Shear Strength		
Field:	Dutch cone penetrometer	ASTM-D3441
	Pocket penetrometer	Soiltest CL-700*
	Standard penetration test	ASTM-1586
	Dilatometic	Soil Instruments, Ltd.*
	Screw plate	B. S. 1377
	Plate load	ASTM-D1194
	Vane Shear	Clayton and others (1982)
	Pressure meter	
	Triaxial field apparatus	Warlam (1961)
	Torvane	Soiltest CL-600*
	Iowa borehole shear test	Wineland (1975)
Laboratory:	Direct shear	ASTM-D3080
	Triaxial	ASTM-D2850
	Unconfined compression	ASTM-D2166
	Swedish fall-core	Hansbo (1957)
	Vane Shear	ASTM-D2573

Continued

Table 8. Continued

	Technique	Reference
Swell/shrink Capacity		
Field:	Magnetic probe extensometer (Swell)	Brown (1970)
	(Collapse)	Soil Instruments, Ltd.*
Laboratory:	Oedometer swell test (one dimensional swell)	ASTM D4546-85 AASHTO T258-81
	Sausage	Jennings and Knight (1975) ASTM D-427-83 ASTM D-4546-85
Bearing Capacity	Bearing capacity	ASTM D-1194-72
Liquefaction Potential		
Field:	Standard blasting test	Florin and Ivanov (1961) Seed and Idriss (1971)
Laboratory:	Cyclic loading triaxial compression	Seed and Peacock (1971)
	Cyclic simple shear	Seed and Lee (1966)
	Ground response analysis	Seed and Idriss (1967)
Collapsibility		
Field:	Simple or multiple rod extensometer	Ghadiali and Tymemms (1981)
	Settlement plate	Soil Instruments, Ltd.*
Laboratory:	Collapse potential	Jennings and Knight (1975)
Settlement Potential	Settlement potential	ASTM-4546-85
	Consolidation test	ASTM-D2435
	Floating ring test	ASTM-D2435
Sensitivity	Unconfined compressive strength undisturbed	
	Unconfined compress strength remolded	
Field:	Vane shear test	ASTM-D2573
	Unconfined compression	ASTM-D2166
Soil Characterization		
Field:	Density - sand core	ASTM D1556 AASHTO T191
	- nuclear	ASTM 2922
Laboratory:	Atterburg limits	ASTM D423 AASHTO T89(U)
	Plastic limit	ASTM D424 AASHTO T90 (PL)
	Shrinkage limit	ASTM D427 AASHTO T92 (SL)
	Particle size analysis	
	- grain size	ASTM D421
	- sieve	ASTM D422 AASHTO T27
	- hydrometer	ASTM 152H AASHTO T88, T27
	Moisture content	ASTM D2216
	Specific gravity	ASTM D854 ASTM C127 AASHTO T100
	Clay mineralogy of less than 2 micron fractions	Hallberg, Lucas, and Goodmen (1978); Killey (1982)

*Equipment no. and/or manufacturer

Shrink-swell. Shrink-swell capacity is the ability of earth materials to increase or decrease in volume with an increase or decrease in moisture content. Associated with swelling is a reduction in strength, bearing capacity, and heave, all of which can result in damage to surface structures. The potential for earth materials to swell or shrink depends both on conditions at the site at the beginning of construction and on changes in stress and moisture content to which the site is eventually subjected.

Factors that directly influence shrink/swell characteristics are:

- the percentage of clay-size material
- the type of expandable clay minerals
- the difference between field moisture content during construction and equilibrium moisture content after completion of construction (This difference is due usually to climatic changes or to the removal of plants.)
- the degree of compaction or consolidation
- the stress to which the material will be subjected after completion of construction (the less the imposed load, the greater the swelling)

Bearing capacity. Ultimate bearing capacity is the maximum load a soil will support before settlement. In some cases, settlement may cause structural damage. Design loads for soils are determined either by taking the ultimate bearing capacity and subtracting a factor for safety, or by determining the maximum load that causes a tolerable settlement. Geologic material conditions and anticipated loads may influence the type of foundation considered.

Liquefaction. Liquefaction is the loss of shear strength in fine-grained, loose, cohesionless sediments, generally less than 15 meters from the surface. It results from excess pore-water pressure caused by natural events such as earthquakes or man-made activities, such as blasting or pile-driving.

Compression. Peat and peaty clay are susceptible to compression under load. To avoid settlement and cracking of structures, these materials should be removed and replaced with suitable soils.

Sensitivity. Sensitivity is a ratio describing the relative loss of strength of earth materials after remolding (disturbance of interior structure). If necessary, sensitive soils should be removed and replaced with suitable materials.

Summary. To evaluate geotechnical properties of materials the following procedures should be performed:

- Evaluate basic earth material properties, including sediment type, texture, chemistry, grain-size distribution, porosity, density, water content, and depth and thickness of strata.
- Evaluate shear strength and bearing capacity of sediments.
- Identify compressible, sensitive (quick), and swelling materials.
- Perform consolidation tests to determine (1) the compressibility of the sediments; (2) the stress history of the material (that is, how much consolidation has already occurred); and (3) the time, rate, and amount of further settlement that can be expected under a given static load.
- Determine the stress distribution of proposed structures in underlying earth materials and compare to the strength properties of the earth materials (i.e., shear strength, bearing capacity, sensitivity). Protection against all possible modes of failure should be considered.
- Delineate potential modes of foundation failure and take the steps necessary to prevent a failure.

GEOCHEMICAL CONSIDERATIONS OF EARTH MATERAILS

In considering the processes of attenuation in the transport analysis of a proposed site, the geochemical characteristics of the earth materials must be determined. The degree of reliance of the site design on these processes is important in determining how much characterization is necessary. For example, to determine whether retardation would result in attenuation of contaminant concentrations to acceptable limits, the distribution coefficients for each contaminant must be determined in field tracer tests or in laboratory tests using samples of earth materials and groundwater from the site.

Ideally, the geochemical environment surrounding the facility will provide maximum stabilization of the longest-lived and/or most hazardous waste component should release occur. Ensuring this level of protection requires detailed information on the geochemical characteristics of the earth materials at the site and the composition of the wastes. Though it is not possible to predict precisely the effects of geochemical processes or attenuation and eventual migration, site selection should attempt to maximize the potential degree of attenuation that would result if contaminants were released from the facility to the environment.

Clay minerals. Geochemical interactions between leachates and surrounding earth materials can significantly reduce contaminant concentrations and retard contaminant migration in groundwater (Griffin and Chou, 1980; Roy and Griffin, 1985; and Roy et al., 1986). Certain contaminants can be removed from the groundwater by being sorbed onto earth materials in the immediate vicinity of the facility. The degree of attenuation depends in part on the geochemical characteristics and clay mineralogy of the materials beneath the facility and on the nature of the contaminant (metals, for example, are generally not very mobile). Because of their chemical makeup, clay minerals have the capacity to significantly exchange or adsorb certain contaminants, thereby retarding migration and allowing decay to occur. Clays influence the adsorptive reaction for virtually all chemicals. Materials with a high clay content provide significantly greater sorption of some contaminants, particularly positively charged ions and compounds, than materials with a low clay content.

Both the quantity and type of clay strongly influence adsorption of radionuclides because many radionuclides are metallic compounds adsorbed as a result of the cation-exchange capacity of the material (Popp et al., 1984). For general siting purposes then, the amount of sorption and effectiveness of this process in retarding migration should be evaluated in terms of both the type and quantity of clay minerals in the materials. Clay minerals with higher sorption capacities, such as smectite, can selectively retain a greater quantity of many contaminants than clay minerals such as illite or kaolinite (Weber and Coble, 1968). It seems desirable, therefore, to locate a waste disposal facility in an area underlain by clays, claystones, or shales; these materials contain clay minerals with an affinity for retardation of contaminants.

Organic content. Because many organic chemicals are non-polar (such as those chemicals present in hazardous waste), little relationship may exist between adsorption and percent clay (Green, 1974). The non-ionic nature of organic carbon, however, causes adsorption of both anions and cations. Organic carbon contained in organic-rich surface soils (paleosols) or within a matrix of glacial materials often plays a major role in adsorbing organic contaminants. Adsorption is highest when the organic content is highest; however, it is still significant when the organic carbon content is as low as 0.1 percent (Lyman, 1982).

HOMOGENEITY/ISOTROPY

A homogeneous geologic unit is a body of geologic material that is relatively uniform in its sedimentologic character (e.g., composition, porosity, grain size, sorting, or bedding), and hydrologic properties (e.g., hydraulic conductivity). In addition, if these material properties are constant with respect to the direction of measurement, the unit is considered to be isotropic.

The homogeneity and isotropy of both individual geologic units and sequences of geologic materials determine the difficulty and, hence, reliability of describing and correlating geologic materials between test borings and excavations. The degree to which a site may be geologically and hydrologically characterized, modeled, analyzed, and monitored will be directly related to the homogeneity and isotropy of materials. Homogeneity and isotropy also control, in part, the variance in the direction and rates of groundwater flow.

Horizontal and vertical determinations of hydraulic conductivity provide the best evidence of anisotropy and inhomogeneity in materials. Directional values of hydraulic conductivity may be determined from oriented core samples (McCray and Nowatzki, 1985). Near-surface determination of potential problems with anisotropic or inhomogeneous materials is best revealed in test pits, where the continuity of materials can be traced.

Homogeneity and isotropy determinations can vary depending upon the scale of observation, for example, whether a sequence or unit of geologic materials is observed in the outcrop, in a hand specimen, or under a microscope. We recommend that sites be avoided for HW or LLRW disposal where the extent and distribution of geologic materials and the flow of groundwater cannot be reliably determined and predicted with a reasonable quantity of available information (from borings, geophysics, and other methods). Both "reliable" and "reasonable" must be determined subjectively; however, the determination should follow a systematic work plan such as that discussed in this report.

Examination of geologic material hand specimens also should be conducted at the proposed site. Examination should identify any inhomogeneous conditions (e.g., changes in permeability, porosity, or lithology) or anisotropic conditions (e.g., fractures or pronounced bedding) that may influence groundwater flow, contaminant attenuation, and engineering properties of the material. Microscopic examination of materials should be conducted when necessary to provide a thorough understanding of their geological and hydrological properties.

FLOOD HAZARD AREAS

Flood hazard areas are adjacent to streams and rivers and are subject to flooding following a storm of a certain magnitude (typically defined by its statistical recurrence interval, e.g. 100 years). Flood waters traversing flood hazard areas may erode protective dikes or undermine surficial containment structures, resulting in damage to or the rupture of a containment system. Such damage could lead to the transport and rapid distribution of large volumes of waste by surficial processes. Flood waters also could infiltrate containment systems and saturate wastes. Periodic wetting and drying of waste containers could facilitate chemical reactions that lead to the release of contaminants. Site inundation also could increase groundwater recharge and subsequently accelerate the potential transfer of contaminants from the site to groundwater resources. Finally, catastrophic floods frequently relocate stream channels within flood hazard areas and, hence, may increase the potential for facility damage by future floods.

Calculations and mapping of the 100-year floodplain are typically subject to numerous uncertainties. For example, records of many basins lack long-range historic data. Also, future changes in climate, hydrology, and land use may affect flood recurrence. Dunne and Leopold (1978) suggest that the width of the 100-year floodplain on maps constructed under favorable conditions may be in error by as much as 30 to several thousand meters.

We recommend that waste disposal restrictions based on the 100-year floodplain be expanded to include regions inundated by waters of the probable maximum flood (PMF), the flood produced by the most critical combination of flood-producing conditions within a watershed (Schumm et al., 1982). The PMF is typically based upon the probable maximum precipitation, worst conceivable antecedent soil moisture and runoff conditions, and unit hydrographs and measurements (if they exist) of the largest flood on record for a watershed. Calculations also should include floodwaters that may result from upstream dam failures. Restricting disposal facilities from regions subject to inundation by the PMF minimizes the potential for site inundation over the containment period. PMFs, however, should be calculated carefully. Schumm et al. (1982) have shown that "on numerous occasions PMFs have been exceeded." This may be attributed primarily to errors in statistical calculation of the probable maximum precipitation.

To guard against inundation, many hazardous waste facilities now include structures designed according to the elevation of the 100-year flood event. Such structures may be useful in protecting facilities from PMFs. However, structure design must also take into account landscape variables, such as rates of channel or valley floor aggradation and changes in channel position. Wells et al. (1985) point out that "channels and valley floors change configuration (i.e., width, depth, and elevation) over time periods ranging from years to thousands of years. Computations of flooding extent based on modern channel configurations may be meaningless given the major changes of channels and valley floors documented in the study." Although these comments referred to channel and valley floor modifications in the semiarid southwest, the general context of this statement is applicable elsewhere, particularly to locations with small gullies or minor streams. Kochel (1988b) should be referred to for assistance in determining whether a stream at or near a candidate site is vulnerable to erosional changes.

An alternative to site selection based on calculating PMFs or other statistical probabilities of flood-prone areas in river valleys is to restrict HW or LLRW disposal facilities from the geomorphic floodplain. Because these areas often are underlain by moderate- to high-yielding aquifers, this approach also helps avoid other potential problems associated with siting in these areas. However, flood-prone areas do occur outside definable stream valleys.

Determination of PMF. Numerous methods have been devised to estimate PMFs within drainage basins, including those of the World Meteorological Organization (1969, 1970, 1974), and Lindsley, Kohler, and Paulhus (1975). These techniques typically require the development of unit hydrographs (the hydrograph of one unit of direct runoff from a storm of specified duration) for the basin of interest, as well as estimates of the probable maximum precipitation (PMP), the probable upper limit of precipitation that can occur in a region given atmospheric moisture content and wind conditions during major storms. Due to the variability of drainage basins, as well as the complexity and subjectivity of PMF calculations, exact PMF estimation methodologies are not presented here. Instead, we recommend that site-characterization studies use procedures that are most suited for the watershed and that are consistent with methodologies described in the cited documents.

Information pertaining to the development of unit hydrographs is found in Lindsley, Kohler, and Paulhus (1975) and Dunne and Leopold (1978). The development of synthetic unit hydrographs for basins with little or no hydrological data is discussed by Rantz (1971), Snyder (1938), and the U.S. Soil Conservation Service (1972). Estimation of the PMP is determined from one of three methods: storm maximization, storm models, and statistical procedures. Storm maximization is described by the World Meteorological Organization (1969, 1974); storm models are discussed in reports of the U.S. Weather Bureau (1956, 1960, 1961); and statistical methods of PMP calculations are found in Hershfield (1961) and the U.S. Weather Bureau (1961).

We also recommend that channel, floodplain, and low terraces be investigated for sedimentologic and stratigraphic evidence of large unrecorded floods. If sedimentologic evidence (e.g., slackwater deposits, overbank gravel sediments, or flood boulder bars) are present, field surveying, paleohydraulic reconstructions, and stratigraphic dating should be performed to estimate the long-term frequency and magnitude of floods at potential sites (Schumm et al., 1982). Examples of the use and implications of sedimentologic and stratigraphic data with respect to flood magnitude are presented in Balog (1978), Costa (1974, 1978a, 1978b), Knox (1979), Kochel (1988a), Kochel and Baker (1988), Ritter (1975), and Williams (1984).

Calculated flood magnitudes, using stratigraphic and sedimentologic data, should be compared when possible to estimated PMFs. If estimated PMFs are less than the flood magnitude determined from stratigraphic/sedimentologic data, the PMF should be adjusted to the higher, more conservative value. But note that evidence of extreme floods has not been preserved in all basins that have been subject to low-frequency, high-magnitude floods.

PROXIMITY TO SURFACE-WATER BODIES

The proximity of a disposal facility to surface-water bodies, such as lakes, streams, wetlands, and man-made reservoirs, influences the potential for contamination of those bodies from runoff and other processes. Contaminants released to any surface-water body may (1) contaminate the impounded water for a considerable period of time during which it will be unusable as a resource and also will release contaminants to downstream water bodies, (2) create a health risk to the environment and population surrounding the water body and downstream, and (3) increase the potential for contamination of other nearby surface-water sources. HW or LLRW disposal facilities should not be sited within the PMF level of any surface-water body.

GROUNDWATER FLOW SYSTEM CONSIDERATIONS

The groundwater system is a significant potential pathway for released contaminants from a HW or LLRW disposal facility. This may result in contamination of groundwater in aquifers and possibly public or private supplies withdrawn from the aquifers. The rate of migration from the facility to the area to be affected is determined by the hydraulic and chemical characteristics of the geologic materials, the physical and chemical properties of the contaminant, biological conditions, and the nature of the groundwater flow system beneath the facility.

The occurrence and movement of water through geologic materials from areas of recharge to areas of discharge constitute a groundwater flow system. Such a system is generically depicted in figure 16. Water enters groundwater flow systems primarily from infiltrating precipitation that moves downward through the vadose zone (unsaturated zone) to the water table. Recharge areas are areas where the net saturated flow of groundwater is directed downward (Freeze and Cherry, 1979). On a regional scale, groundwater generally moves horizontally from areas of recharge to points of discharge. Locally there may be significant downward movement of groundwater (or upward, as in the case of discharge situations).

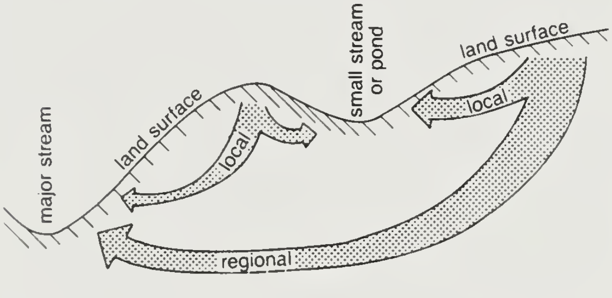


Figure 16 Local and regional groundwater flow systems (from Cartwright and Sherman, 1969).

Critical recharge areas are those regions of rapid natural recharge through permeable soils, which replenish either actual or potential high-yield aquifers of drinking water quality (Illinois Department of Energy and Natural Resources, 1984). Groundwater discharge includes groundwater flow from springs; water seepage into streams, rivers, and wetlands; and evapotranspiration from soils. Groundwater discharge also includes withdrawal via pumpage.

The primary physical phenomena controlling solute transmission are advection, dispersion, and retardation. Advection is the transmission of solutes at the same speed as the average groundwater pore velocity. Dispersion refers to the spreading and consequent dilution of the solute as it is advected through the subsurface. The effects of dispersion allow a dissolved constituent to travel a given distance at a rate greater than the advected velocity. Retardation refers to the chemical and physical mechanisms that delay or slow the movement of solutes in groundwater.

Characterizing site hydrology. A detailed program to characterize the hydrology for a proposed HW or LLRW disposal site should be conducted concurrently with various tasks associated with the description of the site geology. The program should include a determination of saturated zone and vadose zone characteristics, the direction and rate of groundwater movement (vertically and horizontally) and the potential for contaminant transport, and groundwater chemistry. Finally, modeling should be conducted to support inferences made regarding flow paths and travel times and to predict chemical species migration in the subsurface. Characterization of the site hydrology may be a much lengthier process than geological characterization because at least a year is required to evaluate seasonal variations.

Most of this section of the report describes procedures to determine hydrological properties of geologic materials. Hydrological evaluations are essential for characterizing flow through all geologic units at a site. They become particularly important if continuous, highly permeable materials underlie a site. But they are also important if highly permeable deposits are not present. It is still necessary to know the direction and travel time of groundwater in low-conductivity materials. Highly conductive materials may make evaluation much easier because, if present, the site is less likely to be selected for disposal.

The thickness of overlying confining units and rates of flow through the confining unit and within the underlying more-permeable units will ultimately dictate site suitability for waste disposal. The presence of these continuous highly permeable units at relatively shallow depths may warrant exclusion of the site for HW or LLRW disposal. As discussed in the geological characterization section of this report, discontinuous zones of permeable materials (many of which could constitute local low-yield aquifers) also may be present at a site. So long as these materials are localized and do not extend beyond site boundaries, their presence should not necessarily result in exclusion of the site from further consideration. These permeable zones, however, must be monitored, and their hydrological properties and parameters must be thoroughly characterized.

The entire siting process up to this point directs siting away from areas containing high-conductivity materials. However, determination of potential rates of contaminant transmission cannot rely only on tests relevant to transmission capabilities in high-conductivity materials. In low-conductivity materials (i.e., $< 1 \times 10^{-7}$ cm/sec), molecular diffusion may be the primary contaminant transmission mechanism. Tests must be conducted within such materials to determine whether advection/dispersion or diffusion dominate potential contaminant transmission.

Field and laboratory investigations for characterizing a potential site for HW or LLRW disposal must be conducted to evaluate the physical and chemical (including biological) processes that contribute to groundwater and contaminant movement. Elements requiring evaluation include:

- hydraulic head
- hydraulic gradient
- hydraulic conductivity
- transmissivity
- total and effective porosity
- storage coefficient and specific yield
- dispersion
- retardation

The following discussion includes procedural and proscriptive recommendations for determining flow and transport characteristics at a candidate site.

Hydraulic head. Head is defined as the energy contained in a water mass, produced by elevation, pressure, and velocity (Driscoll, 1986). In groundwater systems, this energy is almost entirely potential energy derived from pressure and elevation and is called the hydraulic head (or potential); in a saturated medium, the head at any point is taken as the elevation, usually in feet or meters above mean sea level, of the top of a static column of water that can be supported above the point (Bennett, 1976).

The surface defined by water levels in several wells penetrating a saturated confined formation is called a potentiometric surface. A potentiometric surface may be above or below the water table found in the uppermost, unconfined formation. The water table itself is a potentiometric surface. Where the head varies appreciably with depth in a geologic formation or formations, a potentiometric surface is meaningful only if it describes the head along the particular specified stratum in that formation. More than one potentiometric surface is then required to describe the distribution of head in multiple aquifers.

Hydraulic head is usually calculated by converting a water level measurement (taken as a depth-to-water reading measured from the ground or the top of well casing) to an elevation by subtracting the depth-to-water from the measuring point elevation. A number of methods are used for measuring depth-to-water, including chalked steel tape, electric drop line, air line, pressure transducer, and float apparatus (Garber and Koopman, 1968).

Because the hydraulic head most probably will be different at different locations and depths in most water-bearing formations, it is essential to construct wells or install piezometers so that water levels collected from them are depth-discrete. Leakage of water along the casing should be prevented because it will create a water level that is not representative of the zone of interest. Screening too long an interval (greater than 1.5 to 3 meters) will integrate the head over that interval, giving a measurement that may not correctly indicate the head at any one point within the screened interval.

The use of expanding neat cement and bentonite clay, or a mixture of bentonite clay and neat cement in the drill hole annulus, from just above the screened section to land surface is an effective sealing procedure (Barcelona et al., 1985a). Care should be exercised to keep the grouts and seals away from the screen with a clean sand and gravel-pack. This will avoid clogging of the screen with fine-grained materials and creating interferences with water chemistry should these wells also be used for water-quality sampling.

Head measurements should be collected regularly for at least 1 year during the site-characterization process to measure groundwater response to climatic conditions. Continuous recording devices, such as a float-and-pen-chart apparatus, or short-interval recorders, such as pressure transducers connected to dataloggers, provide the most complete record of variations in groundwater level. Maps of recorded high and low water table conditions should be constructed to give an indication of the zone of fluctuation and the seasonal changes in the depth to the saturated zone. Hydrographs of water levels in wells correlated with on-site measurements of precipitation may be useful. These measurements must be made to provide the information necessary for determining groundwater flow directions and a hydrologic budget for the HW or LLRW disposal site.

Hydraulic gradient. As it flows, groundwater loses energy because of friction against the pore and channel walls of the porous medium along its seepage path. The loss in energy (head) per unit length of distance travelled is called hydraulic gradient (Davis and DeWiest, 1966). The hydraulic gradient is calculated by determining the change in head between two points along a flow path and dividing by the distance between the points at which the heads are measured. The hydraulic gradient, then, is unitless and is often expressed as feet/feet or meter/meter.

Hydraulic gradient is typically separated into two components: vertical and horizontal. In isotropic systems, the hydraulic gradient establishes the direction of saturated groundwater movement and the direction the center of mass of solutes will travel with the groundwater. Geographic regions where the hydraulic gradient is predominantly vertical are areas of recharge or discharge, depending upon the direction of the gradient.

Hydraulic gradient, in association with the hydraulic conductivity, determines the groundwater flux. In an anisotropic aquifer the direction of groundwater flow is not necessarily the same as the gradient; flow direction also is related to the direction of maximum hydraulic conductivity. At least three wells are necessary to define the gradient or slope of a potentiometric surface for determination of the lateral direction of groundwater movement (Pfannkuch, 1981).

"Nested" piezometers, wells located close together but finished at different depths to create vertical separation, are used to determine vertical hydraulic gradients. If the deeper well in a nest contains a lower head than a shallower well, then the hydraulic gradient is such that the potential for groundwater movement is downward. Similarly, if the deeper well contains a higher head than a shallower well, the hydraulic gradient indicates that the potential for groundwater movement is upward. Vertical movement downward from the surface denotes groundwater recharge, whereas upward movement indicates a zone of groundwater discharge.

Hydraulic conductivity. Hydraulic conductivity, the measure of ease in which groundwater moves through a rock or sediment, may vary within any particular geologic formation (table 7). However, if the hydraulic conductivity within a geologic formation is relatively constant and independent of location (i.e., similar in value at different positions throughout the formation), the formation is considered to be homogeneous. In contrast, if hydraulic conductivity varies by position within the formation, then the formation is inhomogeneous (heterogeneous).

Groundwater seepage or pore velocity is a function of hydraulic conductivity, hydraulic gradient, and effective porosity. Therefore, hydraulic conductivity affects the rate of movement of chemical constituents in the saturated groundwater flow system. Thus, all other factors being equal, the lower the hydraulic conductivity, the slower the groundwater flow velocity and, consequently, the rate of potential contaminant migration. The spatial variability of hydraulic conductivity affects the reliability of site-specific groundwater quality monitoring. In general, there will be greater confidence in the ability to detect contaminant migration in a relatively homogeneous, isotropic groundwater system than in a highly variable system.

Hydraulic conductivity is a function of the porous medium as well as the fluid in motion. The hydraulic conductivity of a geologic formation depends on a variety of physical factors, including porosity, particle size and distribution, particle shape, particle arrangement (packing), and secondary features such as fracturing and dissolution. It also depends on the specific weight and dynamic viscosity of the fluid (Davis and DeWiest, 1966; Freeze and Cherry, 1979; Todd, 1980). Under normal field conditions, for unconsolidated materials, hydraulic conductivity values vary with particle size (table 7). Fine-grained, clayey materials normally exhibit lower values of hydraulic conductivity than coarse-grained, sandy materials.

Hydraulic conductivity is related to transmissivity; where highly conductive conditions exist, controlled production or aquifer tests are commonly performed to derive the hydraulic properties of aquifers. In fine-grained materials where conductivities are on the order of 1×10^{-6} cm/sec or less, it is difficult for wells to sustain the constant pumping rates that aquifer tests require. Hydraulic conductivity also may be estimated using a variety of other methods, including laboratory analysis (column permeameter tests) and *in situ* testing (slug tests and borehole dilution tests), or by comparison of subsurface materials with similar materials for which a range of conductivity has already been established (Gass, 1986).

Hydraulic conductivity measurements derived from laboratory testing of subsurface materials (constant-head or falling-head permeameter tests), while useful, have been shown to be as much as one order of magnitude less than field measurements (Herzog and Morse, 1984). The discrepancy between laboratory and field measurements may be due to a number of factors. Samples may be either siltier or sandier than the zone of interest, or naturally occurring fractures in the deposit may not be included in the collected samples. In addition, samples are often remolded during collection or preparation, thus destroying the natural orientation of the grains and altering the value obtained from the laboratory test. Use of distilled water in laboratory tests may not represent *in situ* groundwater conditions; similarly, pressurizing the sample to force water through it may alter the structure of the sample. Finally, laboratory tests typically measure vertical hydraulic conductivity, which may be as much as two orders of magnitude lower than the field horizontal conductivity (Gass, 1986; Todd, 1980).

For these reasons, *in situ* field measurement of hydraulic conductivity is necessary for proper characterization of a proposed HW or LLRW disposal site. The slug test involves the instantaneous change in head in a piezometer by the addition or removal of a known volume of water. It is also possible to create the same effect by suddenly introducing or removing a solid cylinder of known volume (Freeze and Cherry, 1979). A number of methods have been derived for determining the hydraulic conductivity of materials through the use of slug test data (Boersma, 1965; Bouwer and Jackson, 1974; Cedergren, 1967; Cooper, Bredehoeft, and Papadopulos, 1967; Hvorslev, 1951; and Papadopulos, Bredehoeft, Cooper, 1973).

Transmissivity. Transmissivity is the rate at which water is transmitted through a unit width of aquifer under a unit hydraulic gradient (Driscoll, 1986; Todd, 1980). It is the product of hydraulic conductivity and saturated thickness. Transmissivity values are not often of direct use in site investigations where low-yielding, fine-grained materials predominate. It is not transmissivity but hydraulic conductivity that is used to calculate contaminant travel times (along with hydraulic gradient, effective porosity, and the chemical characteristics of the contaminant).

However, tests to determine the transmissivity of a geologic formation are useful for deriving the hydraulic conductivity. Field tests to determine transmissivity are fairly simple, and the theory behind such determinations is well understood. In addition, field tests used to determine transmissivity give values that

Table 9. Representative values of porosity (from Todd, 1980).

Material	Porosity (%)	Material	Porosity (%)
Gravel, coarse	28	Loess	49
Gravel, medium	32	Peat	92
Gravel, fine	34		
Sand, coarse	39	Siltstone	35
Sand, medium	39	Claystone	43
Sand, fine	43	Shale	6
Silt	46	Till, predominantly silt	34
Clay	42	Till, predominantly sand	31
Sandstone, fine-grained	33	Tuff	41
Sandstone, medium-grained	37	Basalt	17
Limestone	30	Gabbro, weathered	43
Dolomite	26	Granite, weathered	45
Dune sand	45		

can be considered to represent larger areas than the point-specific values derived from laboratory or slug tests used for determining hydraulic conductivity.

Aquifer tests (also called controlled pumping tests) are probably the most accurate, reliable, and commonly used method for determining the transmissivity of saturated materials. These tests should be conducted at a proposed HW or LLRW disposal site if it is suspected that permeable materials are continuous. The tests also can be used to estimate the degree of hydraulic communication between layers of earth materials with differing hydrogeologic properties.

The occurrence of a variety of aquifer conditions (including unconfined, confined, composite, and leaky) has resulted in the development of a number of aquifer test methods and an even greater number of methods for data analysis (McCray and Nowatzki, 1985). The theory of groundwater flow and particularly the relationship between pumping stresses on water levels in aquifers and the determination of aquifer hydraulic properties (such as transmissivity, storage coefficient, and leakance) have been discussed by Boulton (1954), Hantush (1956), Jacob (1944 and 1950), Muskat (1946), Theis (1935), Wenzel (1942), and a number of current texts including de Marsily (1986), Freeze and Cherry (1979), and Todd (1980).

Total and effective porosity. Void spaces (i.e., pores and fractures) occur throughout geologic materials. Because these interstices serve as water conduits, they are of fundamental importance to the study of groundwater (Todd, 1980). The relative amount of pore space in a soil is expressed as porosity, which is defined as the ratio of the volume of voids or pores to the total volume of solid. Porosity refers to the total amount of void space without regard to the moisture or air contained in the pores. However, it follows that under saturated conditions, the porosity would be equal to the moisture content of the material.

Porosity is usually expressed as a percentage rather than as a ratio. Representative porosity values for various geologic materials are listed in table 9. It should be noted that the porosity of a particular soil or rock may vary considerably from these values. An examination of the values presented in table 9 shows that some fine-grained materials, such as clay and loess, may contain similar or greater porosities than do some coarse-grained sands and gravels. On the other hand, the hydraulic conductivities of coarse-grained materials are usually orders of magnitude greater than those of fine-grained materials. This difference is due to the amount of interconnection among pore spaces; this allows water to flow.

Porosity and hydraulic conductivity are dependent upon the shape, packing, and size distribution of the constituent particles of the geologic material. Geologic materials composed principally of highly angular, coarse-grained particles, such as some sands or gravels, contain highly connected pore spaces that allow water to be transmitted easily. On the other hand, the flat, platelike structure of clays produces a high porosity, but it also contains voids that are small and not well-connected, resulting in a low hydraulic conductivity.

Effective porosity is the percentage of a material that consists of interconnecting interstices or voids. The smaller the effective porosity the higher the groundwater pore velocity. Fine-grained sediments with low hydraulic conductivity often have small effective porosities, though total porosity may be large. The natural variability of hydraulic conductivity is much greater than the variability of effective porosity.

A principal concern in calculating groundwater travel time is determining what value to use for effective porosity. For coarse-grained materials, the effective porosity approaches, or is equal to, the specific yield of the material (i.e., that portion of a saturated material that will drain by gravity). For fine-grained materials, specific yield values may have little relationship to effective porosity, particularly for materials whose conductivity is on the order of 1×10^{-7} cm/sec or less (these materials hold water by capillarity and do not drain by gravity). Unfortunately, the effective porosity in such materials is extremely difficult to determine by experimental means, and experimental tests of several compacted soils have not provided conclusive results.

Horton, Thompson, and McBride (1985) reported that effective porosities determined by mercury-intrusion porosimetry were five to seven times less than total porosities. On the basis of microscopic observations of three compacted clay liners, Green, Brown, and Thomas (1985) conclude that the effective porosity was substantially less than the total porosity, in some cases less than 10 percent of the total porosity. Unpublished results following Peyton et al. (1986) indicate that when velocities are so slow that molecular diffusion predominates over mechanical dispersion, the effective porosity of the materials tested was identical to the total porosity (using tritium as a tracer).

Intuitively, it would appear that effective porosity must always be less than total porosity, but it is impossible with our present state of knowledge to say by how much. Therefore, travel time calculations in fine-grained materials should be used for general guidance to determine if travel times are on the order of weeks, months, years, decades, or centuries at a proposed HW or LLRW disposal site. Whenever calculations of travel times are made, it should be clearly stated what values were used for effective porosity and the rationale for selecting those values. It might be suggested that ranges of travel times be given based on a reasonable range of effective porosity values, with total porosity as the bound on the longest travel time.

Storage coefficient and specific yield. The storage coefficient is defined as the volume of water that a geologic formation releases from or takes into storage per unit surface area of the formation per unit change in head. The storage coefficient is a dimensionless unit.

The magnitude of a formation storage coefficient depends on whether the formation is confined or unconfined. If the formation is confined, the water released from storage comes from expansion of the water and from compression of the formation as the head declines. The storage coefficients of most confined aquifers range from 1×10^{-5} to 1×10^{-3} cm/sec. If the formation is unconfined, the predominant source of water is from gravity drainage of the sediments through which the decline in the water table occurs.

Specific yield is the term used to describe the amount of water a formation releases through gravity drainage. In unconfined aquifers, the storage coefficient is essentially equal to the specific yield, with values ranging from approximately 0.1 to 0.3. The storage coefficient is commonly derived from data collected during controlled pumping tests. The data also are used to derive aquifer transmissivity.

Storage coefficients and specific yields are important in determining the transient behavior of groundwater systems. The long-term withdrawals of water from a confined aquifer may result in drainage of water from overlying confining beds. If water levels in an area are reduced to the point that an aquifer changes from a confined to an unconfined condition, the storage coefficient of the aquifer in the affected area immediately increases from that of a confined aquifer to that of an unconfined aquifer. The changeover in storage coefficients from confined to unconfined values is of great importance in determining the water level response to groundwater withdrawals.

The determination of a storage coefficient may have limited use in investigations of fine-grained materials not considered to be aquifers. However, under water table (unconfined) conditions, the storage coefficient determined from aquifer test analysis is equal to the specific yield of that material, which, in turn, can also give a reasonable approximation for effective porosity.

Dispersion. Dispersion affects the concentration of a solute that is being transported via groundwater. It refers to solute spreading (at the macroscopic scale) caused by both mechanical dispersion and molecular diffusion (Bear, 1979). Under natural flow conditions, the spreading phenomenon predominantly results from velocity differences due to both microscopic and macroscopic variations in hydraulic conductivity and porosity. Diffusion effects are negligible (except when groundwater pore velocities are extremely low) in comparison to dispersion caused by aquifer inhomogeneities. In homogenous, low-conductivity materials, molecular diffusion may be the dominant mechanism in the transmission of contaminants.

The dispersion coefficient is the fundamental parameter controlling the degree of spreading and dilution of a solute plume (Waldrop, 1985). The dispersion coefficient has a L^2/T unit of measurement and is directional, just as is hydraulic conductivity. Experiments have shown that the dispersion coefficient is proportional to the pore velocity in the direction of mean fluid flow. The proportionality "constant" is called dispersivity and is defined as the characteristic mixing length (Anderson, 1979).

The magnitude of dispersivity (and consequently the dispersion coefficient) is dependent on both length and time scales. The greater the travel distance in a tracer test used to measure dispersivity, the larger the resulting dispersivity value (Anderson, 1979; Molz, Guven, and Melville, 1983). Further, de Marsily (1982) indicates that field-scale dispersion coefficients may also be time-dependent. According to Anderson (1979), laboratory measurements of dispersivities result in values typically in the range of 10^{-2}cm to 1 cm. In contrast, dispersivities determined from field-scale experiments vary from 10 meters to more than 100 meters (Anderson, 1979). Waldrop (1985) also presents dispersivities for several field-scale groundwater flow regimes.

If previously published values of dispersion are not relevant for the particular site undergoing characterization, then some form of tracer test is necessary to determine field-scale dispersivities for calculation of dispersion coefficients. Typically, tracer tests are complicated and expensive. Anderson (1979) provides a detailed overview of both single-well tracer methods and multiple-well tracer methods used to calculate dispersivities. Fundamentally, the procedure involves injecting a tracer into a porous medium and measuring the rate of dispersion by monitoring concentrations of the tracer. The resulting experimental data are fitted to either analytical or numerical solutions of the dispersion equation, and the dispersivities are calculated.

Waldrop (1985) lists the following criteria as important to obtaining highly reliable dispersion values:

- The tracer test must be either uniform flow, diverging radial flow, or a two-well pulse test (without recirculation).
- The tracer input must be well defined in terms of the input concentration and the temporal distribution of the input concentration.
- The tracer must be conservative; that is, unreactive and nonadsorbing (e.g., $C1^-$, I^-, Br^-, and tritium).
- The dimensionality of the tracer concentration measurements must be appropriate (typically three-dimensional).
- The analysis of the concentration data must be appropriate. A one-dimensional analysis is not usually appropriate.

Retardation. Solutes that sorb onto the solid medium are retarded in their movement through a groundwater flow system (Roberts et al., 1985). To include consideration of sorption-controlled retardation of radionuclides or hazardous wastes in predicting their migration from a disposal facility, the retardation factor R_d is used. R_d is expressed as a ratio of the groundwater pore velocity to the chemical species velocity.

The most commonly used quantitative description of ion sorption onto or off of the solid matrix of the porous media is the distribution coefficient, K_d, which is the ratio of the concentration of ions sorbed on the skeletal framework to the concentration of ions in solution (Oberlander, Skaggs, Shafer, 1985). Distribution coefficients are typically determined from laboratory experiments. According to Oberlander et al. (1985) values for K_d are determined by batch (static) experiments or dynamic experiments in which the contaminant flows through a column of porus media. The batch tests result in a representative value for K_d of the chemical species; dynamic column experiments directly measure the retardation. Field-scale experimental determinations of K_d's are much less numerous than laboratory measurements.

The distribution coefficient approach to calculating retardation integrates all the geochemical reactions affecting a specific chemical species present in the groundwater flow system. The use of distribution coefficients to predict field-scale contaminant migration in saturated groundwater has been long established. Even so, its use should be limited to species present in trace amounts undergoing near-equilibrium reactions (Anderson, 1979).

GROUNDWATER MONITORING PROGRAM

Groundwater quality monitoring is an important component of site characterization for a HW or LLRW disposal site. An evaluation of existing groundwater quality sometimes is necessary to establish a benchmark or baseline level against which to evaluate site performance over time. Also, depending on the composition of the waste, it may be worthwhile to determine background water quality for determining the compatibility of the waste with the existing chemical composition of potential receiving waters. For these reasons we have chosen to include a discussion of groundwater monitoring in this report.

Barcelona et al. (1985a) present a number of factors that should be considered in the design and execution of a groundwater monitoring program. Such factors include evaluation of the hydrogeologic setting and program information needs, proper well placement and construction, evaluation of well performance and purging strategies, and execution of effective sampling protocols, which include the appropriate selection of sampling mechanisms and materials, as well as sample collection and handling procedures. Each of these elements should be considered for its potential effect on the chemistry of the sample being collected, and each should be strictly controlled.

Hydrogeologic setting and sampling frequency. The HW or LLRW disposal site must be understood in terms of how the regional and area geology and hydrology may affect groundwater quality (Eccles and Nicklen, 1978). This includes determining (1) the types and distribution of geologic materials, (2) the occurrence and movement of groundwater through those materials, (3) the location of the site in the regional and local groundwater flow systems, (4) the relative hydraulic conductivity of the geologic materials, and (5) the potential interactions between contaminants and geologic or biologic materials. All of this should have been determined when the geological and hydrological framework was established for the site. Although sampling frequency is often dictated by regulation, the minimum sampling frequency can be calculated on the basis of the rate of groundwater movement and the distance or flow path length along which samples are desired (Barcelona et al., 1985a; Casey, Nemetz, and Uyeno, 1983; Nelson and Ward, 1981).

Information needs and analytical selection. The information needs of a groundwater sampling program determine both the scope and details of field and laboratory efforts. Certain hydrological information, particularly water level data, should always be collected. Initial exploratory sampling should include a complete mineral analysis of the water. A consistency check on major ionic constituents (through an ion balance) and in-field determinations (e.g., alkalinity) should be performed, and the potential effects of unusually high levels of metals or nutrient anions

(Keith et al., 1983) should be determined. The results of the complete mineral analysis and field determinations define the major ion solution chemistry, which is necessary to obtain an overall picture of the subsurface groundwater system. The major ion chemistry determines the inorganic background and potential for matrix effects in sampling and analysis.

A number of other chemical factors must be determined to develop a monitoring system capable of detecting a potential contaminant release and the mobility of the contaminant within the groundwater system. These include analyses of trace metals and nonmetals, dissolved gases, organic constituents, and background (possibly naturally occurring) radioactivity. In addition, age-dating techniques (e.g., tritium, carbon-14) can provide information essential to interpreting whether advective groundwater movement or molecular diffusion is dominating the transmission of contaminants within the flow system.

The speciation (the distribution among different chemical forms) of metallic and nonmetallic elements provides information on the oxidation-reduction state of the groundwater and the potential mobility of certain contaminants (Freeze and Cherry, 1979). Depending on the pH and Eh of the water, a dissolved constituent may be present in several forms. For example, the oxidation state and degree of hydrolysis of plutonium are strongly dependent on pH and Eh (Cleveland, 1979).

Metal ions associate with major anions and natural organic matter. Such association may enhance the mobility of radionuclides. For example, Killey et al. (1984) showed that subsurface mobility of cobalt-60 was enhanced by complexation with both natural and synthetic organic compounds. Enhanced mobility of other metal ions and organic pesticides has been observed after the formation of soluble organic complexes with humic substances or organic solvents (Broadbent and Ott, 1957; Duguid, 1975; Griffin and Chou, 1980). The total organic carbon (TOC) concentration may be used to estimate the complexation capacity of groundwater.

The minimum data set for a monitoring program designed for groundwater chemistry characterization should provide a base level of information on hydrological and chemical conditions at a HW or LLRW disposal site. The parameters identified below will permit mass and charge balance checks on the consistency of the data and will provide valuable information on groundwater chemistry, including background concentrations of dissolved groundwater constituents. With this information, "missing" charged constituents (e.g., weak acid anions) or elevated concentrations of other constituents found after the facility is in operation can be identified, possibly indicating contamination. This level of detail also provides the basis for solution chemistry composition calculations; these calculations are important for predicting contaminant speciation, mobility, and persistence. The following chemical parameters should be included in the monitoring program:

- Eh, pH, Ω^{-1}, TDS, Alkalinity, Temperature
- Major anions (Cl^-, NO_3^-, SO_4^{-2}, PO_4^{-3})
- Major cations (Na^+, K^+, Ca^{+2}, Mg^{+2}, Fe^{+2}, Mn^{+2})
- Trace nonmetal species (As, B, Cl, F, N, P, S, Se)
- Trace metal species (Al, Ba, Cd, Cr, Cu, Hg, Fe, Mn, Pb, Zn)
- Dissolved gases (O_2, CO_2, CH_4, H_2S)
- Gross alpha and beta activities (and specific radionuclides of interest)
- Gross organic parameters: total organic carbon (TOC), total organic halogens (TOX), chemical oxygen demand (COD)
- Age-dating constituents (e.g., tritium, oxygen-18/oxygen-16, carbon-13/carbon-12, carbon-14, chlorine-36

Well placement and construction. Decisions about the placement and construction of monitoring wells are among the most difficult in developing an effective monitoring program for a HW or LLRW disposal site. Positioning a monitoring point in a potential contaminant flow path must be done on the basis of hydrological and geological data. Therefore, a number of on-site parameters related to the underlying saturated zone must be determined to calculate the rate and direction of groundwater movement and, ultimately, potential contaminant migration.

Because measurements for many of these parameters will vary over time and location, a statistical treatment is necessary. The mean, median, and range—as well as the temporal and spatial variability of many of these parameters—are needed for proper interpretation of groundwater conditions at a candidate site.

Data collection points must be properly placed so that information collected is representative of the site (Barcelona et al., 1985a; Barcelona, Gibb, and Miller, 1983; Gillham et al., 1983; Wehrmann, 1986). Preliminary locations and depths of points for data collection should be selected on the basis of the best available predrilling data (Barcelona et al., 1985a). The generic test-drilling program outlined in this report and the placement of wells in boreholes should provide adequate data for preliminary characterization of the site hydrology. Additional data collection points should be situated where more information is needed or where long-term monitoring is dictated.

It is important to locate monitoring wells spatially and vertically in such a manner as to ensure that the groundwater flow regime is being adequately investigated. A number of factors governs where and how many wells should be constructed. These include site geology, site hydrology, source and contaminant characteristics, and the size of the area under investigation. The methodology for determining the number and location of monitoring wells should be similar to the designing of borehole placements for geologic site characterization (discussed earlier). Certainly the more complex the geology and hydrology and the larger the area under study, the greater the number of wells required for adequate hydrological characterization of the HW or LLRW disposal site.

Monitoring wells should be constructed in a manner that minimizes the disturbance of the materials in which the wells are constructed (Scalf et al., 1981). Drilling and well completion methods traditionally have been selected on the basis of the type of geologic materials to be penetrated, the anticipated depth of drilling, and the availability of construction equipment and materials. Attention must be given to the potential adverse chemical effects of the drilling and well construction on samples produced from the monitoring well. Detailed discussions of drilling procedures and rigs are presented by Campbell and Lehr (1973), Driscoll (1986), and Scalf et al. (1981). Similarly, much recent research and literature is devoted to proper monitoring well design (Barcelona et al., 1985a; Gillham et al., 1983; Luhdorff and Scalmanini, 1982; and Wehrmann, 1986).

Well development, hydraulic performance, and purging strategy. Once completed, the monitoring well must be prepared for water sampling, and measures must be taken to evaluate the hydraulic characteristics of the well. These steps provide the basis for developing a reliable, long-term groundwater monitoring program. The proper development of monitoring wells is essential to the collection of "representative" water samples. Several development techniques are discussed by Barcelona et al. (1985a), Schalla and Landick (1985), and Wehrmann (1986).

The response of a monitoring well to pumping must be determined in order to assess the proper rate and duration of pumping prior to collecting a water sample. Conductivity tests should be performed on every well in the monitoring system to provide information for recommended sampling procedures and to determine appropriate sampling frequencies for the wells (see section on hydraulic conductivity).

The number of well volumes to be pumped from a monitoring well prior to the sample collection must be tailored to (1) the hydraulic properties of the geologic materials being monitored, (2) the well construction parameters, (3) the desired pumping rate, and (4) the sampling methodology to be employed. No single number of well volumes fits all situations. For low-conductivity materials, usually all that can be done is to initially flush all casing storage water from the well and collect a water sample as the water level in the well recovers. Some experiments have been conducted to examine the effects of not flushing the well at all and immediately sampling the screened zone (Gillham et al., 1983). Extreme care must be used in such situations to avoid mixing sample water with overlying stagnant casing water. Above all, the goal in establishing a well-purging strategy is to obtain water from the geologic materials being monitored while minimizing the disturbance of the local flow system and the collected sample.

Sampling mechanisms and materials. Sampling mechanisms for collecting groundwater samples are among the most error-prone elements of monitoring programs. A number of sources can be consulted for information regarding sampling mechanism design, materials, and their effects on groundwater samples (Barcelona et al., 1984; Barcelona et al., 1985b; and Gillham et al., 1983)

Sample collection protocol. A well-conceived sampling protocol consists of a written description of the actual sampling and analytical procedures involved in obtaining representative hydrological and chemical groundwater data. Unusual occurrences or departures from written procedures should be recorded. The principal steps in the sampling protocol are listed in table 10a. Table 10b includes a goal for each step and a general recommendation for achieving the goal. These general steps are common to all groundwater sampling efforts. Both tables provide a prioritized scheme for the execution of steps within the overall protocol, which should help guide the planning of sampling efforts. Essential elements for ensuring the reliability of each step also are provided in the table to aid planning of specific efforts. Evidence of such a sampling protocol should be included in a quality assurance/quality control plan prepared for groundwater monitoring at the HW or LLRW disposal site or sites being investigated.

VADOSE ZONE STUDIES

The vadose zone is the interval between the ground surface and the top of the permanent zone of saturation. This interval is also referred to as the unsaturated zone; however, because temporary zones of saturation may occasionally develop within this interval, the term vadose zone is preferred. The top of the zone of saturation is called the water table.

Below the water table all pores and openings in the soil or rock are filled with water. Above the water table, in the vadose zone, these pores are only partially filled with water; the remaining pore space is occupied by various gases (nitrogen, carbon dioxide, methane, hydrogen sulfide, and others). This does not mean, however, that water movement does not occur in unsaturated materials. Infiltration of precipitation through the vadose zone is responsible for groundwater recharge. A release of contaminants from a surficial HW or LLRW disposal facility could result in the transmission of those contaminants through the vadose zone toward the saturated groundwater system. Thus simply preventing groundwater contact with the facility does not ensure that contamination will not occur (though it can reduce the potential severity of the release in some cases).

Water table levels. The position of the water table is not constant; its elevation varies in response to several factors, including seasonal effects from precipitation, recharge and discharge, and prolonged evapo-

Table 10a. Generalized flow diagram of groundwater sampling steps (from Barcelona, et al., 1985a).

Step	Procedure		Essential Elements
Well Inspection	Hydrologic Measurements		Water-Level Measurements
Well Purging	Removal of Isolation of Stagnant Water		Representative Water Access
	Determination of Well-Purging Parameters (pH, Eh, T, Ω^{-1})**		Verification of Representative Water Sample Access
Sample Collection Filtration* Field Determinations**	Unfiltered	Field Filtered*	Appropriate Mechanism
			Minimal Sample Handling
	Volatile Organics, TOX		Head-Space Free Samples
	Dissolved Gases, TOC		"
	Large Volume Samples for Organic Compound Determinations		Minimal Aeration or Depressurization
		Alkalinity/Acidity**	Minimal Air Contact, Field Determination
Preservation Field Blanks Standards	Assorted Sensitive Inorganic Species NO_2^-, NH_4^+, Fe(II)	Trace Metal Samples	Adequate Rinsing against Contamination
	(as needed for good QA/QC)	S^-, Sensitive Inorganics	Minimal Air Contact, Preservation
		Major Cations and Anions	
Storage Transport			Minimal Loss of Sample Integrity Prior to Analysis

* Denotes samples which should be filtered in order to determine dissolved constituents. Filtration should be accomplished preferably with in-line filters and pump pressure or by N_2 pressure methods. Samples for dissolved gases or volatile organics should not be filtered. In instances where well development procedures do not allow for turbidity-free samples and may bias analytical results, split samples should be spiked with standards before filtration. Both spiked samples and regular samples should be analyzed to determine recoveries from both types of handling.

** Denotes analytical determinations which should be made in the field.

transpiration. Water table elevations also may be affected by groundwater pumpage. The observed range in elevation of the water table throughout an average annual cycle is referred to as the zone of fluctuation.

The present site-suitability requirements for LLRW disposal (see appendix) indicate that "the disposal site must provide sufficient depth to the water table that groundwater intrusion, perennial or otherwise, into the waste will not occur." The USNRC will consider an exception to this requirement to allow disposal below the water table if it can be shown conclusively that the characteristics of the materials in the vicinity of the facility result in very slow rates of groundwater flow and contaminant transport such that molecular diffusion would be the predominant means of contaminant movement and that the rate of movement would ensure that performance objectives are met. In no case should disposal of wastes be permitted in the zone of water table fluctuation. Alternate wetting and drying may cause soils to fracture and also enhance leaching.

Seasonal fluctuations of the water table and the capillary fringe immediately above must be considered in site-characterization studies for HW or LLRW disposal. The thickness of the capillary fringe (which is essentially saturated but below atmospheric pressure) is difficult to determine but can be quite extensive in fine-grained earth materials. During parts of the year,

Table 10b. Generalized groundwater sampling protocol (from Barcelona, et al., 1985a).

Step	Goal	Recommendations
Hydrologic Measurements	Establishment of nonpumping water level.	Measure the water level to ± 0.3 cm (± 0.01 ft).
Well Purging	Removal or isolation of stagnant H_2O which would otherwise bias representative sample.	Pump water until well purging parameters (e.g., pH, T, Ω^{-1}, Eh) stablize to ± 10% over at least two successive well volumes pumped.
Sample Collection	Collection of samples at land surface or in well-bore with minimal disturbance of sample chemistry.	Pumping rates should be limited to $\sim$100 mL/min for volatile organics and gas-organics and gas-sensitive parameters.
Filtration/ Preservation	Filtration permits determination of soluble contituents and is a form of preservation. It should be done in the field as soon as possible after collection.	*Filter:* Trace metals, inorganic anions/ cations, alkalinity. *Do not filter:* TOC, TOX, volatile organic compound samples. Filter other organic compound samples only when required.
Field Determinations	Field analyses of samples will effectively avoid bias in determinations of parameters/ constituents which do not store well: e.g., gases, alkalinity, pH.	Samples for determinations of gases, alkalinity, and pH should be analyzed in the field if at all possible.
Field Blanks/ Standards	These blanks and standards will permit the correction of analytical results for changes which may occur after sample collection: preservation, storage, and transport.	At least one blank and one standard for each sensitive parameters should be made up in the field on each day of sampling. Spiked samples are also recommended for good QA/QC.
Sampling Storage/ Transport	Refrigeration and protection of samples should minimize the chemical alteration of samples prior to analysis.	Observe maximum sample holding or storage periods recommended by the Agency. Documentation of actual holding periods should be carefully performed.

the capillary fringe and even the water table may rise almost to land surface, particularly in low-relief areas with low-permeability sediments. Water infiltrating into a facility in these areas could accumulate within the waste, eventually spilling out onto the surface or into the shallow subsurface adjacent to the facility. This phenomenon is known as the bathtub effect. To eliminate this problem, the infiltration of water must be restricted enough so that water can be drained from the bottom of the facility at least as rapidly as it infiltrates through the top. Leachate collection systems and engineered covers are two techniques that can remedy the problem.

Characterizing the vadose zone. Evaluating the characteristics of the vadose zone is a necessary part of hydrologic site characterization. Because any contaminant must travel through this zone to the zone of saturation, monitoring the vadose zone may provide an early warning of site failure and migration of wastes (Berg, Morse, and Johnson, 1987). However, characterizing the hydraulic and geochemical properties of the vadose zone and monitoring water or contaminant movement in the zone are not easy tasks. The properties that control water and contaminant migration in unsaturated materials are much more complex and less predictable than those applicable to the saturated zone.

Several recommendations pertaining to data collection and characterization of the vadose zone are:

- *The surface of the seasonal high water table and the thickness of the capillary fringe should be defined.* This should be done for the entire site and for adjacent areas that could impact groundwater levels beneath the facility.
- *The zone of fluctuation of the water table should be determined for the site.* This will require careful description and characterization of the materials in the vadose zone beneath the facility.
- *The hydraulic and chemical properties of the vadose zone should be determined.* These should include (1) the natural water content (chemical nature and volume), (2) the relationship between water content and capillary pressure for each type of earth material, (3) the saturated hydraulic conductivity and the relationship between water content and unsaturated hydraulic conductivity for each material (the latter term is variable and dependent on water content), and (4) the geochemical properties of the materials.
- *Disposal above the highest expected water table is most desirable.* The distance between the base of

a facility and the highest expected elevation of the water table cannot be specified without considering site conditions; it must be based on observations of the probable maximum height of the water table. These observations must include detailed characterization of the earth materials beneath the facility to identify indications of previous saturation (e.g., mottling). These observations will provide valuable information regarding the presence of groundwater and rates of water movement. Another important factor is the maximum height of the capillary fringe. Disposal structures should be above this height. It is very difficult to determine the exact depth to the capillary fringe and its zone of fluctuation. Therefore, it may be difficult to determine precisely the interval to be maintained between the base of the facility and the capillary fringe.

- *The disposal of waste below the water table, in saturated materials, is not inherently undesirable.* More important are the rates at which water and contaminants are transported in groundwater. Rates of groundwater and contaminant transport are governed by the hydraulic conductivities and effective porosities of earth materials, rather than whether or not materials are saturated. In fact, fine-grained earth materials that naturally have very low hydraulic conductivities are often very nearly saturated even when located above the water table. This is due to the very high water-holding capacity of the small pores in fine-grained materials. The water table is commonly very shallow in these areas, which are inherently more suitable for waste disposal because of their low hydraulic conductivity.

The determination of water table characteristics and the nature of the vadose zone is best evaluated during the geological characterization of the site using test pits and boreholes. The relationship between moisture content and hydraulic conductivity must be carefully determined for each type of material and soil type in the vadose zone.

Parameters needed to determine the hydrology of the vadose zone include porosity; specific yield and specific retention; moisture content; moisture potential; moisture characteristic curves; fluid conductivity; hydraulic conductivity; infiltration capacity; flux; velocity of fluid movement; thermal gradients; and vapor transport. These parameters are discussed in detail by McCray and Nowatzki (1985). Their suggestions should be followed in determining vadose zone characteristics.

Chemical properties of soil-water in the vadose zone may affect interactions between contaminants and earth materials through attenuation of contaminant migration. This phenomenon is best evaluated in field tracer tests or in column tests, both of which must utilize undisturbed samples of earth materials from each geologic unit at a candidate site. Extreme care is required to minimize the disturbance of geologic samples during collection and testing. Groundwater samples from each undisturbed geologic unit must also be used in the tracer tests. The methodological approach to conducting such investigations is presented by Roy et al. (1986).

Monitoring the vadose zone. The monitoring of water quality in the vadose zone is best accomplished by using a lysimeter, a soil-water sampling device (Johnson and Cartwright, 1980). The design for placement of soil-water samplers should be done only after the exact location proposed for waste storage has been determined at the site. Soil-water samplers should be located beneath this location, as well as around the perimeter of the waste. It is important that an overabundance of samplers not be installed immediately below the waste so as not to compromise the integrity of the site. The number and placement of soil-water samplers at the site perimeter will vary depending on the geometry of the waste disposal area.

In regions of a thick vadose zone, more than one soil-water sampler can be nested at different depths in one shallow bore hole, provided that sealing is adequate between the samplers. In regions of a thin vadose zone, only one shallow soil-water sampler may be necessary to monitor unsaturated water conditions.

Many techniques have been formulated for monitoring the quality of water in the vadose zone. Lengthy discussions of these methods are presented by Everett et al. (1976), Fenn et al. (1977), and Richards (1949).

GROUNDWATER MODELING

Groundwater modeling plays an important role in the overall evaluation of the suitability and acceptability of proposed HW or LLRW disposal sites. A properly designed and implemented site-specific groundwater modeling study can aid in (1) organizing data pertaining to site hydrogeology, (2) determining the completeness of field and laboratory data for the site, and (3) assessing the performance of the site under various facility design scenarios. There are four fundamental categories of groundwater modeling, each addressing different physical phenomena (Mercer and Faust, 1981). The four categories are flow modeling, solute transport modeling, heat transport modeling, and structural deformation modeling (i.e., land subsidence).

Flow and solute transport modeling are particularly important to HW or LLRW disposal siting. Groundwater models can be subdivided into physical, electric analog, or mathematical models. It is the last of these that is of primary importance to HW or LLRW disposal siting.

The groundwater modeling process requires a feedback approach whereby continued data collection efforts are used to improve the model in a stepwise manner (Mercer and Faust, 1981). Before beginning groundwater modeling of the site, the objective(s) of the modeling program must be well conceived and clearly understood. The three basic steps in groundwater modeling are: (1) conceptual modeling, (2) mathematical modeling, and (3) sensitivity studies (Harrison et al., 1985).

Conceptual modeling. A conceptual model is a qualitative description (e.g., pictorial and/or narrative) that represents relevant components and structures (i.e, physical boundaries to flow, lakes and streams, wells) occurring within the groundwater system, the interaction between components and structures, and all internal and/or external processes (e.g., recharge, pumpage) that affect system performance (Harrison et al., 1985). Conceptual models provide the link between performance scenarios and mathematical models for performance assessments. Consequently, as the conceptual model becomes more complicated, the less desirable the site becomes from the standpoint that it cannot be quantitatively modeled with acceptable accuracy. The requirement that the site be accurately modeled results from the need for predictability.

Site predictability must be determined before the consequences of various hazardous contaminants or radionuclide release and transport scenarios can be estimated numerically (i.e., mathematically modeled) with satisfactory confidence. Sites characterized as having fractured or solution-controlled flow are highly unpredictable.

Mathematical modeling. Once the conceptual model of site-specific groundwater flow and contaminant transport is completed, mathematical models can be selected. These models should be consistent with the complexity of the conceptual model, the objectives of the modeling effort, and the available data.

Javandel, Doughty, and Tsang, (1984) describe three different levels of increasing complexity and sophistication used to mathematically model flow and solute transport in groundwater systems. These levels are:

1. Simple analytical methods making a simplified idealization of the flow domain and providing qualitative estimates of groundwater flow and contaminant transport.
2. Semi-analytical techniques providing flow paths for steady-state fluid flow and corresponding contaminant movement in the presence of an arbitrary number of hydraulic sources and sinks. An "average" hydrogeological environment is assumed.
3. Sophisticated numerical models, accounting for complex geometry and heterogeneous, anisotropic media, as well as dispersion, diffusion, and chemical retardation processes (i.e., sorption, precipitation, radioactive decay, ion exchange, and degradation).

A hierarchical approach to site modeling of the groundwater system is recommended. The conceptual model may indicate that a sophisticated numerical model is unwarranted. Also, particularly in the early stages of site characterization, the lack of data may not justify a complex model. Ideally, data collection and analysis should be integrated with model development (Mercer and Faust, 1981). This approach ensures compatibility between model sophistication and available site hydrogeological data.

Sensitivity studies. Sensitivity studies should be used to determine the relationship between groundwater flow and contaminant transport predictions resulting from specific sets of input conditions and requirements for additional data (Harrison et al., 1985). Changes in model predictions should be evaluated in relation to changes in key model parameters (e.g., hydraulic conductivity). Determining the sensitivity of the model to changes in certain parameters helps reduce prediction uncertainties. For example, a sensitivity analysis of groundwater travel time should focus on the sensitivity of groundwater velocities along the expected travel path to the distribution of hydraulic conductivity values over the area being modeled. Knowledge of the sensitivity of the travel time calculation to the distribution of hydraulic conductivity could provide guidance to site characterization. The likelihood of increased parameter information reducing uncertainties in the prediction of travel time would be determined (Harrison et al., 1985).

Data requirements for groundwater modeling. Mercer and Faust (1981) categorized the data requirements for a predictive groundwater model. They separate data requirements into three groups: (1) data describing the physical framework, (2) data describing the stresses on the system, and (3) data pertaining to other factors. Within each group, data requirements are further categorized according to whether they support groundwater flow prediction and/or solute transport prediction. The following list summarizes the data needs for groundwater modeling.

Physical framework

Groundwater Flow

- Hydrogeologic map showing areal extent, boundaries, and boundary conditions of all aquifers under investigation
- Topographic map showing surface-water bodies
- Water table, bedrock configuration, and saturated thickness maps
- Hydraulic conductivity map showing aquifer and boundaries
- Hydraulic conductivity and specific storage maps of any confining beds
- Map showing variation in storage coefficient of aquifer
- Relationship of saturated thickness to hydraulic conductivity
- Relationship(s) of any stream(s) and aquifer (hydraulic connection)

Solute Transport (in addition to the above)

- Estimates of the parameters that comprise hydrodynamic dispersion
- Estimates of the parameters that comprise geochemical retardation for the contaminants of interest
- Waste decay rates
- Effective porosity distribution
- Background information on natural concentration distributions (water quality) in aquifer
- Estimates of fluid density variations and relationship of density to concentration
- Hydraulic head distributions
- Boundary conditions for concentrations

Stresses on groundwater system

Groundwater Flow

- Type and extent of recharge areas (irrigated areas, recharge basins, recharge wells, etc.)
- Surface-water diversions
- Time-varying groundwater pumpage
- Streamflow (if applicable)
- Precipitation
- Evapotranspiration

Solute Transport (in addition to the above)

- Time and space relationship of water quality in aquifer
- Stream-flow quality (if applicable)
- Contaminant source release, concentration, and rate estimation

Other factors

- Information on the local water supply
- Legal and administrative rules
- Environmental concerns (other than site integrity)
- Planned changes in regional water and/or land use (Mercer and Faust, 1981)

Errors in model use are usually due to inadequate data supporting the attempted level of modeling sophistication. Occasionally, errors occur as the result of the misapplication of models (Wood et al., 1984).

Model application. There is no single approach to model application that can be recommended. Modeling methodology must be adaptive and flexible. However, the flow diagram in figure 17 shows the basic components and interrelationships of the mathematical modeling process. History matching (i.e., model calibration) is extremely important. The model calibration phase quantitatively establishes the degree of accuracy to which a groundwater flow system can be modeled. Unacceptable history matching may be indicative of deficiencies in hydrogeological data. Adequate calibration of a groundwater flow model should be a precursor to solute transport modeling.

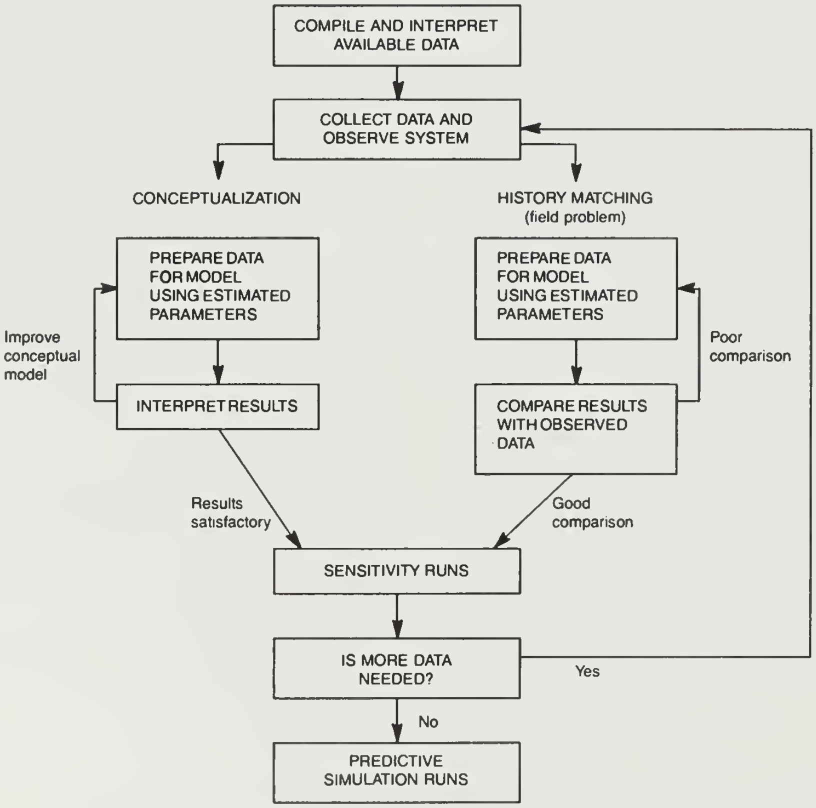


Figure 17 Flow diagram of mathematical modeling process for groundwater systems (Source: Mercer and Faust, 1981).

SITE COMPARISON EVAULATION

Should more than one site meet all of the requirements for disposal of HW or LLRW, then site comparison factors related to geology/hydrology should be used to determine which site has the most favorable of these attributes for potential disposal. Site comparison factors favor certain geological and hydrological factors over others, such that optimization of environmental protection is considered. More favorable comparison factors indicate good overall site performance; however, less favorable conditions do not necessarily exclude a site or sites from consideration for disposal.

The site comparison attributes are separated into two categories: Rank I attributes are more important than Rank II attributes because they have potentially greater impact on contaminant transport to accessible environments. Sites containing Rank I comparative attributes include:

(1) Sites with the greatest groundwater travel time to an accessible environment.
(2) Sites containing thick sequences of high clay content materials.
(3) Sites with the least potential for collapsible, sensitive, and swelling materials and materials with liquefaction potential.
(4) Sites with the greatest horizontal distance from an aquifer.
(5) Sites with materials that are minimally fractured.
(6) Sites containing the thickest sequence of geologic materials and at the same time providing a simple groundwater flow system.
(7) Sites with less than 5 percent slope but greater than 0 percent so that ponding of surface water will not occur.
(8) Sites with minimum previous drilling operations.
(9) Sites farthest from karst features.

Sites containing Rank II site comparative attributes include:

(1) Sites with the fewest minor inactive faults in bedrock materials.
(2) Sites with surficial materials of highest shear strengths and bearing capacities.
(3) Sites with the greatest depth to the permanent water table.
(4) Sites with the lowest relief surrounding a facility.
(5) Sites located farthest from channelized flow or surface-water bodies within the drainage basin area.
(6) Sites with earth materials of low infiltration rates but not susceptible to erosion.
(7) Sites outside of seismic risk areas VIII, IX, and X.
(8) Sites lacking recoverable mineral resources.
(9) Sites with the poorest quality of groundwater.

Site comparison factors should not be rated beyond the above technical classification scheme because local geological and hydrological conditions may result in any one criterion dominating the comparison. If this occurs and, for example, one site has been subject to numerous previous drilling activities and the quality of plugging is suspect, then consideration would go to an alternate site. For many of the factors, site comparison relies on which site is closest or farthest from a condition or which site is more or less favorable to a condition.

We suggest that sites be evaluated subjectively with respect to each of the comparison factors; however, Rank I attributes should be given more weight than Rank II attributes. Assuming there is not the overwhelming preponderance of any one factor at a particular site, then each site should be evaluated for each comparison factor within Rank I and Rank II. The site meeting the largest number of criteria in the Rank I category should be selected for disposal. If sites still remain similar, then Rank II attributes should be considered, and the sites meeting the largest number of Rank II criteria should be selected. Political, social, and economic factors must be brought into the siting process. However, discussions of these important factors are outside the scope of this report.

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APPENDIX

(10 CFR Part 61.50, 1988)

1. The disposal site shall be capable of being characterized, modeled, analyzed and monitored.
2. Within the region or state where the facility is to be located, a disposal site should be selected so that projected population growth and future developments are not likely to affect the ability of the disposal facility to meet the performance objectives . . . .
3. Areas must be avoided having known natural resources which, if exploited, would result in failure to meet the performance objectives . . . .
4. The disposal site must be generally well drained and free of areas of flooding or frequent ponding. Waste disposal shall not take place in a 100-year floodplain, coastal high-hazard area or wetland, as defined in Executive Order 11988, Floodplain Management Guidelines.
5. Upstream drainage areas must be minimized to decrease the amount of runoff which could erode or inundate waste disposal units.
6. The disposal site must provide sufficient depth to the water table that groundwater intrusion, perennial or otherwise, into the waste will not occur. The Commission will consider an exception to this requirement to allow disposal below the water table if it can be conclusively shown that disposal site characteristics will result in molecular diffusion being the predominant means of radionuclide movement and the rate of movement will result in the performance objectives . . . being met. In no case will waste disposal be permitted in the zone of fluctuation of the water table.
7. The hydrogeologic unit used for disposal shall not discharge groundwater to the surface within the disposal site.
8. Areas must be avoided where tectonic processes such as faulting, folding, seismic activity, or vulcanism may occur with such frequency and extent to significantly affect the ability of the disposal site to meet the performance objectives . . . or may preclude defensible modeling and prediction of long-term impacts.
9. Areas must be avoided where surface geologic processes such as mass wasting, erosion, slumping, landsliding, or weathering occur with such frequency and extent to significantly affect the ability of the disposal site to meet the performance objectives . . . or may preclude defensible modeling and prediction of long-term impacts.
10. The disposal site must not be located where nearby facilities or activities could adversely impact the ability of the site to meet the performance objectives . . . or significantly mask the environmental monitoring program.

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